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MINERALOGY

MINERALOGY

AN INTRODUCTION TO THE SCIENTIFIC STUDY OF MINERALS

BY

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WITH TWO COLOURED PLATES AND 716 ILLUSTRATIONS IN THE TEXT

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FEB

PREFACE

THE student will not find in the following pages any systematic account of the modes of occurrence of minerals, their geological distribution, their origin, their alterations, or their artificial reproduction, although these constitute the most important, and, perhaps, the most interesting section of Mineralogy proper. There are no chapters upon these subjects because, in my opinion, they deserve to form a separate volume, and cannot be treated adequately in a volume dealing with the characters and properties of minerals. The essential characters of a mineral, moreover, are quite independent of its source or previous history, and may well be made the first and separate object of study.

In the description of mineral species the modern text-book often endeavours to give too much information, and ends by becoming a book of reference rather than a treatise which can be *read* by the student. This should no longer be necessary, now that Dana's *System* and Hintze's *Handbuch* are available; in the present volume an attempt is made to select for the student all that he requires for an elementary acquaintance with the subject. The species described are those which he will find in all museums, and most of them he may collect for himself. The customary lists of localities are replaced by a description of a few typical occurrences for each important species; by a careful study of the corresponding specimens the beginner should obtain the information which will enable him to pursue the subjects of geological and chemical mineralogy with some previous knowledge of minerals. The few angles given are generally only such as are sufficient for the calculation of the axial ratios or for simple exercises in the calculation of indices.

In the discussion of optical characters, the introduction of two ellipsoids may appear unnecessary and even confusing; the Fresnel Ellipsoid has been introduced in order to avoid incorrect statements about optic axes, but it will be found that the indicatrix is the only ellipsoid subsequently employed.

It cannot be too strongly impressed upon the student at the outset that scientific mineralogy is based upon accurate measurements and determinations, and, accordingly, it is to the intelligent use of the goniometer and microscrope that his attention is mainly directed in the following pages. In this connection it is hoped that the tables on

pp. 551-561 will be useful as leading the student to determine minerals by characters which can be accurately measured.

I have employed the names used by Dana, and have in general adopted his angles and other data, in order to assist the English-speaking student for whom Dana's *System of Mineralogy* is the obvious book of reference, and I have not hesitated to borrow largely from that work.

Maskelyne's *Morphology of Crystals*, Lewis's *Crystallography*, and Brush and Penfield's *Determinative Mineralogy*, will give the student detailed information concerning crystallography and the qualitative analysis of minerals.

Most of the mineralogical names given to the classes of crystal-symmetry are those employed by Dana in his *Text-book of Mineralogy*, and were adopted by us as the result of a correspondence on the subject of nomenclature. The other names (*e.g.* dihexagonal equatorial, etc.) given on p. 280 have been introduced with the object of supplying a nomenclature which expresses the physical symmetry of a crystal as well as its external form.

For kind help in the revision of proofs I have to thank my former colleagues, Mr. G. T. Prior and Mr. L. J. Spencer of the British Museum, Mr. H. Hilton of Magdalen College, and above all Mr. H. L. Bowman, Demonstrator in Mineralogy, to whom I owe more valuable advice and assistance than I can ever adequately acknowledge. My thanks are also due to Mr. L. Fletcher for permission to reproduce specimens in the British Museum, to Mr. T. C. Hepworth for photographs of some of these specimens, and to Mr. A. Hutchinson for some unpublished optical constants.

The shaded drawings of minerals are a new feature, and have been skilfully made from specimens in the British Museum or at Oxford, by my sister, Miss J. Miers, to whom also many of the crystal figures are due. Many of the remainder have been drawn by my assistant, Mr. R. Graham.

I regret that the expense of three-colour collotype printing has rendered it impossible to reproduce in colours more than one interference figure. The plates have been executed at the Oxford University Press, and successful experiments have shown that it is possible to reproduce by this process all the varieties of dispersion and also the interference colours of a quartz wedge.

HENRY A. MIERS.

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INTRODUCTION

1. **A Limitation of the Term "Minerals."**—By the term Minerals are generally understood the materials which constitute the solid crust of the earth: now such materials may consist either of inorganic substances, such as granite, or of organic substances, such as coal. In the latter case their study will involve some acquaintance with the methods of organic chemistry. Further, they may, like granite, have originated quite independently of living animals or plants, or they may, like coal or chalk, have been produced through the life or the decay of such organisms. In the latter case their study will involve some acquaintance with biological methods.

In the present volume it is proposed to exclude from consideration the whole class of organic materials and also those which, though inorganic in their composition, have been produced by organic agencies. The latter class comprises the materials which have been secreted by or have formed part of living organisms. The above limitation, therefore, relieves us of the necessity of taking any account of vital processes in our study of minerals, or of entering into any biological problems. Chalk, pearls, and diatomaceous earth, though inorganic in composition, will be excluded as consisting of the shells, secretions, or skeletons of living organisms; coal, amber, and guano will be excluded on account of their organic composition as well as their mode of origin; petroleum will be excluded on account of its organic composition alone, although its origin may have been entirely unconnected with the life or decay of any organism.

There is no logical reason why the gases and liquids of the earth's crust should not be described in a treatise on Mineralogy, together with the solid materials, since the solid, liquid or gaseous condition of a substance depends merely upon the temperature and pressure to which it is subjected; indeed the ice of the Polar regions has every claim to be regarded as a *solid* portion of the earth's crust. The only liquids which necessarily find a place in any complete survey of the mineral kingdom are mercury and water, but these possess little special interest in relation

to the general study of minerals, and in fact their mineralogical description is incomplete unless account be taken of the characters which they exhibit when solid, so that the word *solid* has been used above in referring to the crust of the earth.

2. **Of the Essential Properties of Minerals.**—Those pieces of mineral matter which are found to possess the same properties are said to belong to the same "kind" of mineral; the number of mineral kinds is very limited: only about 800 are known which are really definite; and all the rocks and stones of the earth's crust which are not simple minerals are made up of some of these kinds mixed in various proportions. Under whatever conditions minerals are found, and in whatever way they have been produced, certain properties belong to each, and are shown by every specimen of it, and it is by these properties that each kind of mineral is accurately defined.

It is therefore necessary to study first the properties of each mineral, and the object of the present volume is to indicate how this is effected. The exact study of minerals has only been developed in recent years, since the discovery of methods by which their properties may be readily and accurately determined. Previously it was customary to distinguish them by their colour, lustre, hardness, fracture, and by superficial characters, some of which, though easily observed, are not capable of exact measurement, while others are even variable in different specimens of the same mineral. In the present state of our knowledge, no one property in itself is sufficient to distinguish a given mineral from all others; it is highly probable that when means have been discovered of determining the chemical constitution completely, in the sense in which it is possible for some of the carbon compounds of organic chemistry, this alone will be sufficient, and all the other properties will be deducible from it; but at present we are forced to employ at least two properties, namely the chemical composition (percentage composition, see p. 198) and the crystalline form; these two, when completely known, are necessary and sufficient for the definition and determination of any mineral.

Two or more minerals may have the same chemical composition (*e.g.* rutile and anatase) and yet differ in all other essential properties; two or more minerals may have the same form (*e.g.* salt and fluor) and yet differ in all other respects; but if they possess the same composition and the same form, they will of a certainty possess in common also other properties —which we may henceforth call the "essential" properties—and will therefore be said to belong to the same mineral kind.

Those characters of minerals which vary among different specimens possessing the same form and composition are not essential: far too great importance has generally been assigned to them in the definition and identification of mineral kinds; such characters are structure, "habit," colour, and the form of mineral aggregates.

3. **Of the Two Sorts of Essential Properties.**—The essential properties of minerals, as of all crystallised substances, are of two sorts.

Firstly, those which do not involve any particular direction, but represent the nature of the substance in the aggregate; such are the density,

the specific heat, the chemical composition; and, secondly, those which are measured in some definite direction.

Take, for example, the properties relating to heat; the specific heat is accurately measurable, but not in any particular direction; a piece of rock crystal has the specific heat 0·1881, but we cannot speak of a direction of specific heat. On the other hand, the expansion for a given rise of temperature can be measured in a definite direction.

Thus a sphere (Fig. 1) cut out of rock crystal whose natural shape is shown in Fig. 2, when heated uniformly, becomes converted into the oval figure or spheroid of Fig. 3, in consequence of the unequal ex-

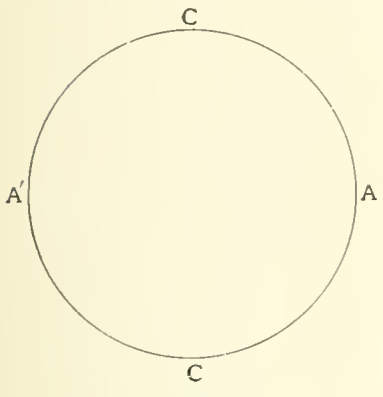


Fig. 1.

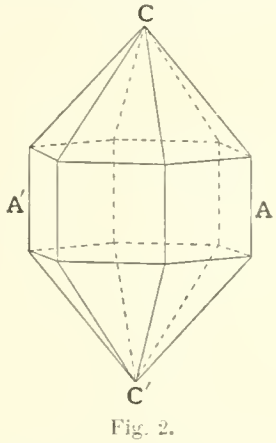


Fig. 2.

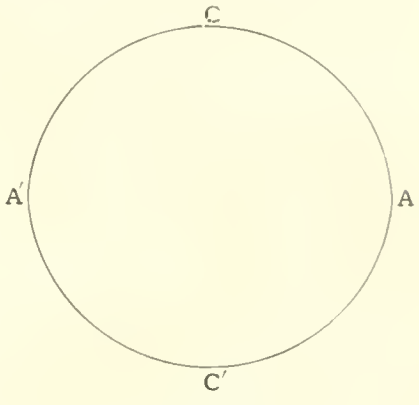


Fig. 3.

pansions in different directions, and these might be ascertained by measuring the exact dimensions of the spheroid. It would be found that the expansion of the rock crystal along such directions as AA′ has been twice as great as that along CC′.

Hence a distinction may be made between the *general* properties and the *directional* properties; to the former belong the density, the specific heat, the temperature of fusion, and the chemical composition; to the latter belong the cohesion, elasticity, and a number of the optical, thermal, electric and magnetic properties, as well as the crystal form.

4. **Of the Two States in which Minerals Occur.**—When the directional properties of minerals are examined it is found that different specimens may behave in one of two ways. In a uniform piece of a single mineral either (1) all the directional properties are the same in every direction, or (2) some of them vary with the direction.

In the former case the mineral is said to be "amorphous," and in the latter it is said to be "crystallised."

Opal, for example, which has a composition not very different from that of rock crystal, differs conspicuously from it in being amorphous. Thus a sphere of opal does not, like rock crystal, become a spheroid when heated, but remains a sphere, because its expansion is the same in all directions.

An amorphous mineral has no characteristic shape. Each crystallised mineral has a characteristic shape, and a mineral exhibiting its characteristic shape is called a "crystal." Fig. 2 is the characteristic shape of rock crystal.

But minerals when crystallised do not always occur in such separate single crystals. The behaviour of ordinary sugar illustrates the various possibilities. If it be allowed to separate slowly from solution, sugar makes its appearance in separate tablets, each of which is a single "crystal." But ordinary loaf sugar is neither amorphous nor a crystal; the properties of a lump of such sugar are apparently the same in every direction, but the lump is not amorphous for it is not really homogeneous; it may be broken up into a number of minute fragments, each of which is part of a single crystal. Hence it is evident that a crystallised mineral need not always show its characteristic form, for it may be a mass consisting of a number of crystals so aggregated together as to interfere with each other and obliterate their characteristic forms by mutual contact. Such a mass is said to be "crystalline." Fig. 4 shows the appearance presented under the polarising microscope by a slice of crystalline quartz (or quartzite)—the same material which in the form of Fig. 2 is known as rock crystal. It is generally necessary, if a mineral behaves like an amorphous substance, to examine it with the microscope in order to ascertain whether it is not really a mass of minute crystals, in which case it is termed "microcrystalline."

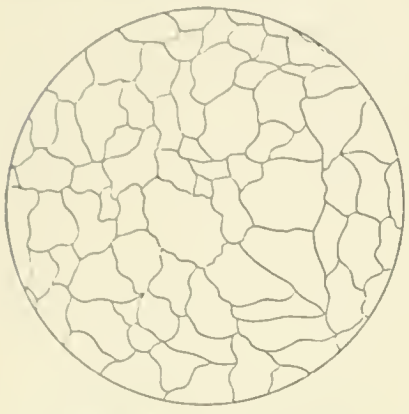


Fig. 4.—Section of Quartzite.

Hence, finally, the two states in which a mineral may occur are—

(1) **Crystallised**, when the mass as a whole or each grain of which it consists exhibits properties which are different in different directions but the same in parallel directions.

(2) **Amorphous**, when it does not exhibit properties which vary regularly with the direction. In this case the mineral is either a powder (like ochre) or a glass (like opal).

A mineral can only exhibit these regularly varying directional properties when it is crystallised. Without them it may be impossible to distinguish between two different minerals which have the same composition, since the general properties only give the nature of the substance in the aggregate, and may not differ sufficiently for the purpose, just as in chemistry it may be impossible to distinguish between two isomers having nearly the same reactions and melting point, unless they can be obtained in crystals.

It is reasonable to suppose that the particles of which a crystal consists are placed side by side in some regular arrangement, like the men in a battalion of soldiers; whereas in an amorphous substance they have no regular order. Without some such hypothesis it is impossible to understand how the properties of a crystal vary regularly with the direction. It is, moreover, in complete accordance with what we know of the growth of crystals; when a substance crystallises in passing from solution or from the liquid condition to the solid state the crystal increases in size by the

constant addition of fresh material to the surface; this is totally unlike the growth of living matter, and can only be explained as due to the deposition of layer after layer of minute particles; and since neither the characteristic form nor the physical properties are changed as the crystal grows, it must be supposed that the particles continue to be deposited with the same regular arrangement.

Since the crystalline characters as well as the chemical composition are necessary for the complete definition of a mineral, the crystallised condition is obviously the only one in which a mineral can be completely investigated, although it may exist in either state.

5. **Of the Scientific Study of Minerals.**—The history of mineralogy began with the development of mining and of the decorative arts; in the search for useful and ornamental materials the nature and the properties of the more common minerals were discovered.

The metalliferous nature of certain ores, the brilliancy and hardness of certain precious stones, were thus brought to light; the use of some minerals as sources of useful products, such as lime, plaster of Paris, glass, etc., of others as pigments, of others again for their medicinal virtues, led to the study of their properties. It became necessary, further, to investigate their modes of occurrence and the characters by which they may be recognised in order that it may be known where they are likely to be found, and how they are to be distinguished when found.

About the beginning of the present century the time came, just as it comes in the history of every science, when mineralogy became a study carried on for its own sake, in a systematic way, with the object of discovering the general laws which it illustrates.

Mineralogy is not, like physics or chemistry, devoted to the study of particular laws, but rather of particular materials, and scientific mineralogy is the accurate investigation of minerals in all their aspects —not merely of the qualities which are useful for industrial and artistic applications. It is therefore the function of the mineralogist to examine every portion of the earth's crust; to determine all the properties of every mineral, whether common or rare; to classify and compare them with the purpose of ascertaining how they resemble each other, and how they differ. With this wide object in view he leaves no method of research untried; and the study of purely scientific mineralogy has consequently, like all scientific research, discovered many useful and suggestive properties which would have been overlooked in any mere attempt to satisfy present needs. It has thus contributed very largely to chemistry, physics, and geology—to chemistry, for example, by the discovery of new elements and compounds; to physics by the investigation of the optical and electrical characters of such minerals as Iceland spar, rock crystal, and tourmaline; to geology by the microscopical identification of the rock-forming minerals necessary in order to understand the genesis of rocks.

One important branch of scientific mineralogy is the study of the modes and places of occurrence of minerals, their origin and the changes to which they are subject. This is to a large extent an entirely

independent subject, except in so far as it throws light upon the nature of the minerals themselves; it is, moreover, a study which should succeed that of the essential properties of minerals, for the essential properties do not vary with the origin or the modes of occurrence; the chemical composition and the form are constant for each mineral wherever, whenever, and however it may have originated.

For this reason the present volume deals almost exclusively with the essential properties of minerals and the methods by which they are investigated; and will only mention their natural modes of occurrence, their origin, and their alterations so far as they contribute to our knowledge of the properties.

From what has been said above it will be clear that the properties of minerals could only be adequately investigated in crystallised specimens, and that the accurate and complete study of minerals could only be established with the aid of a science of crystallography.

Further, the physical and geometrical properties of crystals can be investigated without necessitating their destruction, whereas the chemical composition can only be ascertained by the analysis or destruction of the material; it is therefore natural to begin our study of the essential properties with the former, and to learn how to investigate the nature of a mineral as far as possible before destroying it.

As the Abbé Haüy (who was the originator of crystallography as a science) remarks in his *Traité de Minéralogie* (1801)—"S'il est des cas où le minéralogiste ne peut se dispenser de dire au chimiste: *Apprenez-moi ce que vous venez d'analyser*, il en est d'autres ou le chimiste, pour être prudent doit dire au minéralogiste: *Apprenez-moi ce que je vais analyser.*"

Accordingly we proceed at once to the geometrical and physical properties of minerals before considering their general properties and the nature of their various kinds.

PART I

THE ESSENTIAL PROPERTIES OF MINERALS

BOOK I

THE CRYSTALLINE PROPERTIES

CHAPTER I

ON THE CRYSTALLINE FORM OF MINERALS

1. **Crystals.**—Most substances when allowed to solidify slowly, either from solution, or from the liquid condition, or from a state of vapour. assume characteristic forms, enclosed by plane surfaces; these are called crystals; the substance in solidifying is said to crystallise, and the plane surfaces of a crystal are called its faces. Familiar instances of these three modes of crystallisation are: (1) the crystals of salt or borax deposited from solutions of those substances when the water in which they are dissolved is allowed to evaporate slowly; (2) the crystals of sulphur which encrust the sides of a crucible containing fused sulphur when a portion of the cooling mass is poured off; (3) the brilliant crystals which are formed on the sides of a bottle containing camphor; these last are due to the gradual volatilisation of the camphor and its condensation from a state of vapour.

Crystals may also be formed in any of these three ways when a substance originates from the combination or decomposition of other substances; as, for example, when a crystalline precipitate is produced by the mixture of two solutions.

Most minerals are, sometimes at least, found as crystals; quartz or "rock crystal" occurs in the form of a hexagonal prism terminated

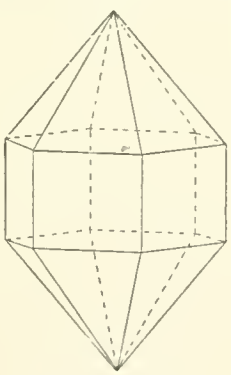


Fig. 5.—Quartz.

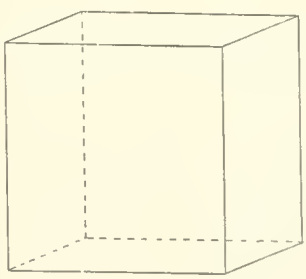


Fig. 6.—Fluor-spar.

by hexagonal pyramids (Fig. 5); fluor-spar in cubes whose six faces are squares (Fig. 6); spinel in regular octahedra whose eight faces are

equilateral triangles (Fig. 7); garnet in "rhombic dodecahedra" whose faces are twelve rhombs (Fig. 8); each mineral has its own characteristic crystalline form.

Fig. 7.—Spinel.

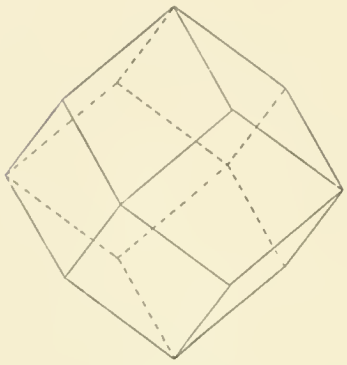


Fig. 8.—Garnet.

As was said above, the form of a crystal is supposed to be due to the orderly arrangement of the particles, just as the form of a military square is due to the orderly arrangement of the men; in solution, and in the liquid or gaseous condition the particles are supposed to be free to move in all directions; in the solid they are supposed to be confined by the constraining action of the neighbouring particles, so that each can only move to a limited extent about a fixed position and may be regarded as practically stationary. The essential form of the crystal is, as might therefore be expected, found to depend upon the nature of the substance and not upon the conditions under which it crystallised; it is quite distinct from any other form which the mineral may be compelled to assume or into which it may be cut. A solution of borax cannot yield crystals having any other than the form characteristic of borax, neither can fluor-spar or garnet assume spontaneously the form of quartz or calcite.

2. **Constancy of Angle.**—Although the crystalline form of a given mineral is characteristic and constant, it must not be supposed that it always has a shape which presents the same appearance to the eye. Spinel has just been said to crystallise in "regular octahedra." Now the regular octahedron of geometry is the figure whose faces are eight equal equilateral triangles; it is the only figure which can be constructed from eight such triangles, and if cut across any one of its edges in a plane perpendicular thereto the section would have the angle $109^\circ\ 28\frac{1}{4}'$; yet the octahedron of spinel, though it always has eight faces, may assume a variety of irregular forms according to the relative sizes and shapes of its faces, as shown in Figs. 9 and 10. How then can the spinel crystal be called an octahedron? A closer examination will show that these variations in form are due merely to differences in the *sizes* of the faces; in both figures the directions of the faces are unchanged, for they are parallel to those of the regular octahedron which is represented by dotted lines within them; and a perpendicular section across any one of the octahedron edges would still give the angle $109^\circ\ 28\frac{1}{4}'$. Both Fig. 9 and

Fig. 10 are called regular octahedra, because their faces are parallel to those of the regular octahedron, and make with each other the angles of the regular octahedron, although the faces are not of the same size. They

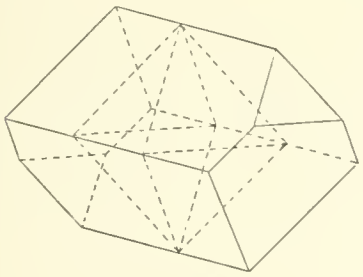


Fig. 9.

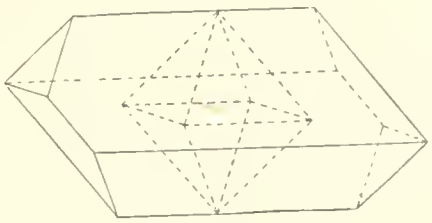


Fig. 10.

Mis-shapen Octahedra.

may be called "mis-shapen" octahedra. Striking examples of such mis-shapen figures among minerals are the delicate fibres of cuprite, known as chalcotrichite, which are in reality elongated cubes of great length in comparison with their breadth. The variations from the ideal figure in mis-shapen crystals are found to be due to the conditions under which the crystals are formed. If, for example, a growing crystal be so situated that it can grow more readily in one direction than in others, it will become elongated in that direction.

The form which a crystal assumes by virtue of the *relative sizes* of its faces is called its "habit"; thus an octahedron may assume a "tabular" or (Fig. 10) "prismatic" habit according as it becomes a tablet or a prism by the enlargement of two or of four of its faces; but variations of habit do not indicate any change in the real form of a crystal.

The constancy of angle was proved in the case of quartz in 1669 by Nicolaus Steno, the famous Danish physician, geologist, and theologian; he found by cutting sections across the crystals that the angles of corresponding sections were the same however the crystal might be mis-shapen. This was the first successful attempt to discover any law regulating the forms of crystals. A century later Romé de l'Isle laid the foundations of crystallography by examining an enormous number of minerals and other crystallised substances; he was able to show that each could be referred to a certain characteristic form which he called the

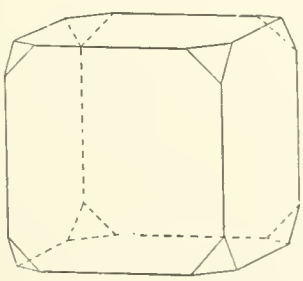


Fig. 11.

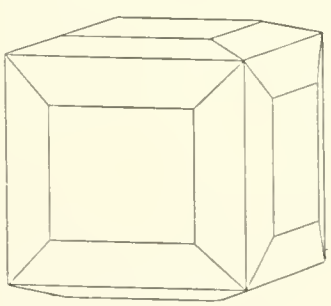


Fig. 12.

Cubes with secondary faces.

"primitive form," and that all crystals of the substance either had the constant angles of the primitive form, or consisted of the primitive form

bearing other so-called secondary faces upon its corners and edges. Thus, the cube is the primitive form of fluor-spar, and crystals of fluor-spar are either simple cubes or have secondary faces derived from the cube in a regular manner (Figs. 11 and 12).

3. **Use of Geometrical Methods.**—There are five "regular solids" known in geometry (octahedron, cube, tetrahedron, regular dodecahedron, icosahedron), each of which is bounded by a certain number of equal equilateral and equiangular faces. Of these figures the first three are to be found among crystals, but, as we have just seen, the corresponding faces of the natural crystal are not necessarily the same, either in size or shape.

There is, however, a sense in which they may be called similar faces; thus all the planes of a cube of fluor are found not only to have the same mutual inclinations, but, further, to be identical in their *physical characters;* they possess the same hardness and lustre; they behave in the same way when exposed similarly to the action of the same agents, such as heat, light, and electricity; they are similarly affected by the same solvents; in this sense also the eight faces of a spinel octahedron, or the twelve faces of a garnet dodecahedron are *similar* faces.

Different faces of a crystal may differ in colour, brilliancy, smoothness, etc. (see Figs. 76, 447, 494), but those faces which are really similar are identical in these respects.

In order to discover which are the similar faces on a mis-shapen crystal all such physical characters must be taken into account. In fact it is evident that the study of crystals is not merely a branch of geometry; to ascertain which faces are really similar it is necessary to examine not only their angular relations, but also their physical properties.

On the other hand, the study of the crystalline form of a mineral may be conducted by purely geometrical methods, if all the similar faces be represented by planes of identical shape and size; in other words, when the crystal has been idealised into a geometrical figure in which *physical* similarity is indicated by *geometrical* identity of shape and size. In this sense Fig. 7 is an ideal representation of both the spinel crystals of Figs. 9 and 10, for its eight faces are identical in size and shape, just as those of the spinel are identical in their physical features. In the same way fluor-spar, whatever its aspect, is said to crystallise in cubes when it is bounded by six *similar* faces at right angles to each other; and garnet is said to crystallise in rhombic dodecahedra when it is bounded by twelve *similar* faces inclined at equal angles to each other.

But it must not be forgotten that the ideal or geometrical figure is only a representation of the physical reality.

When a crystal has grown under uniform conditions it sometimes assumes almost exactly the perfect geometrical figure, all its similar faces being geometrically identical, *i.e.* having the same shape and size. Rhombic dodecahedra of garnet, and octahedra of magnetite are often almost geometrically perfect.

4. **Cleavage.**—Of all the physical characters of a crystal, the curious

property of cleavage is one of the most important, and is the most easily observed. Many crystals, when struck with a hammer, or pressed with the blade of a knife or with a sharp point, break up by separating along certain planes. Mica (often wrongly called talc) and gypsum may be easily split into sheets of any desired degree of thinness. Diamond not only *crystallises* in octahedra (Fig. 7), but also always splits or *cleaves*, when struck, along surfaces parallel to the eight faces of the octahedron: a fact of which the diamond splitters and cutters often take advantage. The octahedron cleaved out of a diamond crystal will not necessarily have all its faces of the same size, but it may be easily reduced to the ideal geometrical octahedron by flaking away slices parallel to the smaller faces until they are all made equal. The cleavage planes are often perfectly smooth and have a brilliancy of surface like that of natural crystal faces, which cannot be imitated by any artificial polish.

Since now any crystal of diamond can be split with *equal* facility along four plane surfaces inclined to each other at the angles of the regular octahedron, these four planes, together with the four planes parallel to them, constitute the eight similar faces of a regular octahedron, and the diamond is said to have an *octahedral* cleavage. If the four cleavages did not take place with equal facility they would not represent similar planes, and therefore could not belong to the *regular* octahedron. Further, it is found that the cleavage takes place parallel to the natural faces of the diamond crystal, and not to any other set of planes inclined to one another at the octahedron angle.

Similarly a cube of galena can be split with equal facility parallel to all its six faces and may thus be subdivided into small cleavage *cubes;* galena is therefore said to cleave parallel to the faces of the cube, or to have a *cubic* cleavage (Fig. 37).

Cleavage had been observed at a very early date and was studied by Bergmann (1773), but this property acquired a new importance in the researches of the Abbé Haüy of Paris; he (1784) was the first to observe that all crystals of the same substance possess the same cleavage, and was led by this observation to a theory of crystal structure which explained all the known facts and first raised the study of crystals to the dignity of a science. His own account of the discovery is as follows—"The fundamental idea of my whole theory was suggested to me by an observation which I made upon calcareous spar in six-sided prisms terminated by two hexagonal faces (see Fig. 13). I had noticed that a crystal of this variety, having been detached by chance from a group, was broken obliquely across in such a way that the fracture presented a clean surface, having the lustre which may be recognised as nature's polish (Fig. 14). I then endeavoured to obtain from the same prism sections in other directions, and after several attempts succeeded in obtaining from each side of the prism three oblique sections (Fig. 15); by new sections parallel to the first I removed from the centre of the prism a rhomboid precisely similar to Iceland spar (see Fig. 16). Struck with this observation, I took other calcareous spars . . . and I found in them the same rhomboidal kernel which had been

yielded by the prism mentioned above. Similar trials made upon crystals of several different kinds soft enough to be smoothly divided gave me kernels which had other shapes, but of which each was invariable in the same kind of crystal."

Fig. 13.

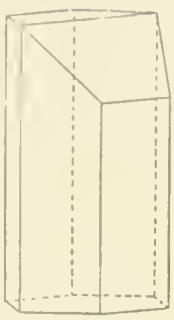


Fig. 14.

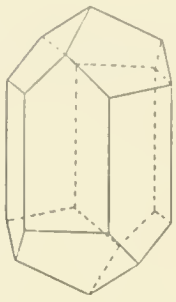


Fig. 15.

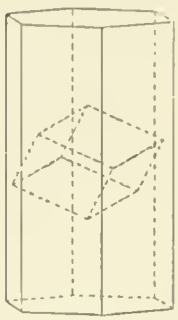


Fig. 16.

The Cleavage of Calcite.

The theory of crystal structure which Haüy based on these observations is alluded to below (p. 21); at present we are only concerned with the fact that calcite has a characteristic cleavage which is not parallel to the hexagonal prism in crystals of that form.

In the octahedron of diamond and the cube of galena the cleavage was parallel to the natural faces of the crystal, but this is not necessarily the case. A crystal may have one form and its cleavage figure may have another. Fig. 17 represents a cube of fluor-spar in which the corners have been split off by cleavage; each corner has thus been replaced by a

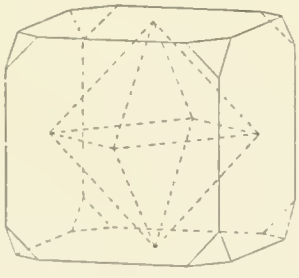


Fig. 17.

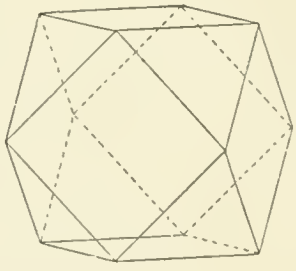


Fig. 18.

The Cleavage of Fluor-spar.

new triangular plane which has removed three equal lengths from the cube edges meeting in the corner; this process may be continued by cleaving away more and more from each corner until the form of Fig. 18 is obtained; finally, if the cleavage be carried on so far that the new faces meet in points at the centre of each cube face, the original crystal will be converted into the regular octahedron which is represented in Fig. 17 as inscribed in the cube. Hence the octahedron can be derived from the cube by the cleavage of fluor-spar, and this mineral is said to crystallise in cubes but to have an octahedral cleavage.

5. **Combinations.**—The crystal of Fig. 18 consists both of cube and octahedron faces, and is called a "cubo-octahedron"; such a figure may

result not only from cleavage but also from natural growth; fluor-spar, for example, usually crystallises in cubes, but may also crystallise in cubo-octahedra, each identical with a cubo-octahedron obtained by cleaving away the corners of a cube.

Crystals which combine two or more such simple figures are called "combinations"; thus Fig. 17 is a combination of the cube and octahedron. Fig. 18 is the same combination in which the octahedron faces are larger. In a combination of two or more figures the predominant figure is said to have its edges and corners "replaced" or "modified" by the smaller faces of the other figures.

In the language of Romé de l'Isle the predominant faces are those of the primitive figure, the others are secondary faces which modify its corners and edges. He found, for example, that fluor-spar could be referred to the cube as primitive figure, and that among the secondary faces of fluor-spar were to be found those of the octahedron.

6. **Symmetry.**—There are many ways of cutting an octahedron out of a cube, but it will be seen from Fig. 17 that the cleavage octahedron supplied by nature from a cube of fluor-spar is the only one which can be *symmetrically* derived from the cube; its faces are parallel to those of the inscribed octahedron. This is found to be a universal law; the cleavage figure is always one which can be symmetrically derived from the crystal itself; and, further, in any combination each figure always has its edges or corners symmetrically modified by the faces of the other.

Now a geometrical figure is symmetrical when every part of it is similar in form to one or more other parts; the geometrical cube has eight similar corners, six similar faces, and twelve similar edges. In the same way the crystal cube has eight similar corners, six similar faces, and twelve similar edges; here, as before, the word *similar* must be understood to mean identical in physical properties and in mutual inclinations, but not necessarily identical in shape or size.

If, then, a crystal of fluor-spar is to be called a cube, it must have the symmetry of the geometrical cube, and its eight corners must be identical in all their physical characters; if one corner can be removed by a single cleavage plane equally inclined to the cube faces, the remaining corners must be capable of the same cleavage, and the cleavage figure must be an octahedron. A crystal having the appearance of a cube, which could be cleaved upon one of its corners, but not upon all, would not be called a cube, for it would not have the physical symmetry corresponding to the geometrical cube.

It is the same with the growth of the secondary faces; if one corner of a crystal cube is replaced by a face of the octahedron, all its corners must be so replaced, and it becomes a complete combination of the cube and octahedron.

The simple law of symmetry which governs all the features of crystal growth may be thus stated: *similar parts of a crystal are similarly modified.* If certain secondary faces are present upon one corner or edge of the crystal, precisely similar secondary faces will be found upon all the similar corners or edges.

It is this law which gives regularity and beauty to the manifold variety of forms belonging to a given mineral, and renders it possible to explain the most complicated and apparently capricious crystalline growths as symmetrically derived from a simple primitive figure.

The exact relations between the secondary faces derived from the primitive figure were discovered by Haüy, and will be explained below (p. 25), but it will already be clear that in any one mineral only certain figures can enter into combination. For example, calcite breaks up very readily by cleavage into the rhombohedron of Fig. 19, and whatever may be the form of the crystal this same rhombohedron will be derived from it by cleavage, as shown in Fig. 39.

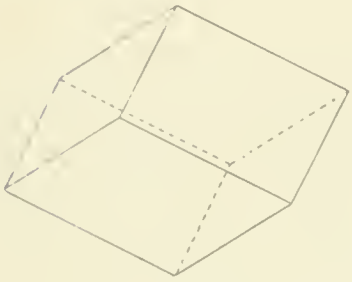


Fig. 19

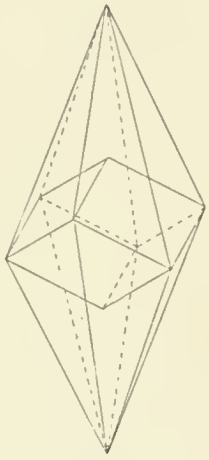


Fig. 20.

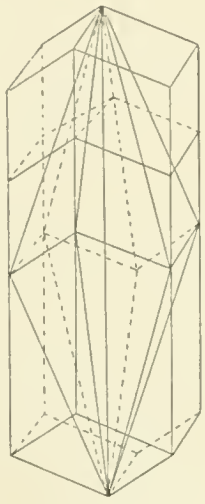


Fig. 21.

A frequent form of calcite (the variety common in Derbyshire and known as "dog-tooth spar") is that of Fig. 20, and the cleavage rhombohedron is here represented as symmetrically inscribed within it. This rhombohedron is itself one of the forms in which calcite crystallises and is regarded as the primitive form; Fig. 20 can be symmetrically derived from Fig. 19, but since it cannot be symmetrically derived from the cube, it can never occur either as a crystal or as a cleavage form in any mineral which crystallises in cubes. Fig 21, copied from Bergmann, shows very clearly how far these facts had been recognised by him as early as 1773. The figure shows two crystals of calcite, a prism terminated by rhombohedron faces, and the form of dog-tooth spar, and indicates how from either of these by cleavage the rhombohedral kernel of Fig. 20 can be obtained.

7. **Planes of Symmetry.**—There are many ways in which a figure may be symmetrical; for example, by a spiral repetition of its parts, as in a circular staircase, or in the whorls of plants; but crystalline symmetry is of a quite distinct character. We must, of course, in studying the symmetry of form imagine our crystal to be geometrically perfect, and to have its similar faces equal in size. Such a crystal is, in the first place, enclosed by plane faces; secondly, it may possess a centre of symmetry, or be "centro-symmetrical," so that any line drawn through the centre

would meet the crystal in similar points at its two ends; thirdly, it may be divisible into two equal halves by bisection along a plane through the centre. (Other possibilities are discussed below, pp. 36, 44.)

Such a plane of bisection has, corresponding to every point of the crystal, a similar point situated at the same distance upon its opposite side, and is called a plane of symmetry. If one-half of the bisected figure be placed against a mirror, the missing half is restored by the reflection; a plane of symmetry then is one over which the features of a crystal are repeated as though by reflection, and bear the same relation to each other which an object bears to its image.

A crystal which can be cut into two such equal halves in only one way has only one plane of symmetry, but many crystals have more than one such plane. The cube possesses the highest degree of symmetry possible among crystals, and has nine such planes; it may be bisected along

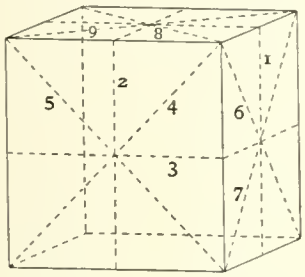


Fig. 22.—Symmetry-planes of Cube.

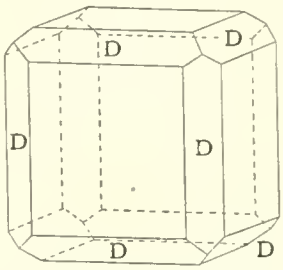


Fig. 23.—Combination: Cube and Dodecahedron.

each of the three planes (1, 2, 3) parallel to its faces, and also along each of the six planes (4, 5, 6, 7, 8, 9), passing through a pair of opposite edges (Fig. 22, cf. also Fig. 74).

A natural crystal may have its faces of any size and various shapes, and may *appear* quite unsymmetrical, but the symmetry will be evident when it is converted in imagination into a geometrically perfect crystal. Choose any point as centre, replace each set of similar faces by planes parallel to them and equidistant from the centre; in this way a symmetrical figure will be constructed, in which the planes of symmetry of the crystal may easily be recognised; the dotted octahedron of Figs. 9 and 10 is derived thus from the misshapen figure. Crystallographic models are made after this fashion, and their planes of symmetry may easily be found by simple inspection. In this book the crystals are generally drawn not misshapen but in "equipoise," so that the similar faces are of the same size, in order that the symmetry may be more apparent.

8. **Forms.**—Any group of crystal faces obtained by modifying all the similar parts of a crystal in the same way, is called a "**form.**" These faces must also be similar to each other, and hence a form may equally well be defined as a complete group of similar faces upon any crystal.

Starting with the cube (which is one form), the eight faces obtained by evenly cutting away the corners constitute a form distinct from any

other such symmetrical group; the octahedron is, then, one form derived from the cube.

Again, if one edge of the cube be replaced by a secondary face D equally inclined to the two cube faces which meet in that edge, then every edge of the cube must be similarly replaced by virtue of its symmetry (Fig. 23). If the cube be cut down parallel to these planes until it is entirely replaced by the new form, the latter is found to be the dodecahedron of Fig. 8. The dodecahedron, then, is a second form derivable from the cube, like the octahedron, and Fig. 23 is a combination of the cube and the dodecahedron.

Every crystal is either a simple form or a combination of two or more forms; and the symmetry of a crystal is the same as that of the figure from which its forms are derived.

9. **Derivation of Forms from the Cube.**—We may now discover all the forms which may belong to a mineral (for example, fluor-spar) by starting with a known crystal of the mineral, such as the cube, and replacing its edges and corners in imagination by a process akin to cleavage. This is the manner in which a wooden model of any form is most easily made: a primitive figure having been constructed in which all the similar faces are of the same shape and size, a new form is derived by modifying in the same way all the similar edges or corners. This may be done in the following three ways:—

(1) *Truncation.*—When two similar faces meet in an edge, that edge may be replaced by a plane equally inclined to them (it must bear the same relation to the two faces, since they are similar, and therefore must make the same angle with each); or a corner in which three or more similar faces meet may be replaced by a face equally inclined to them. The new face is then said to "truncate" the edge or corner.

(2) *Bevelment.*—When two similar faces meet in an edge, that edge may be replaced by a pair of planes *equally* inclined to them respectively. The new faces are then said to "bevel" the edge.

(3) *Replacement.*—An edge or a corner may also be replaced by a

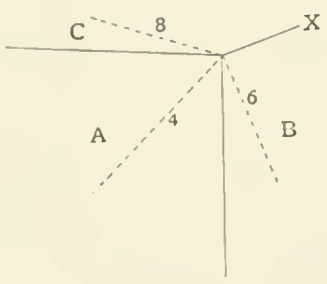


Fig. 24.

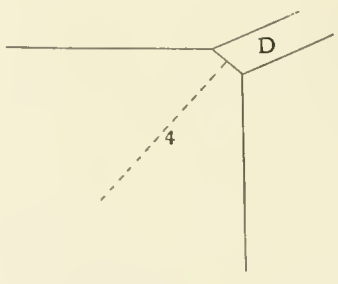


Fig. 25.—Truncation.

plane *unequally* inclined to them; the new face is then said simply to "replace" the edge or corner.

Thus if Fig. 24 represent one corner of the cube with its planes

of symmetry, the edge X is truncated by D in Fig. 25 and bevelled by TT in Fig. 26, and the corner is replaced by x in Fig. 34.

It will now be easy from these principles to construct all the possible forms of fluor-spar from the cube as primitive figure; they are found to be six in number, as follows :—

(1) **Octahedron.** Fig. 7.—The form derived by truncating each cube

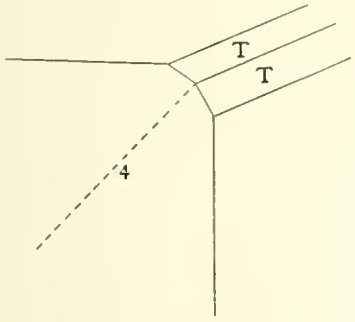


Fig. 26.—Bevelment.

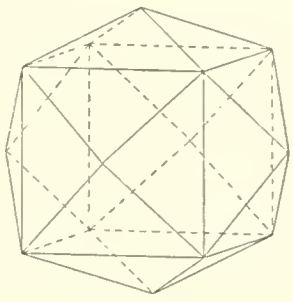


Fig. 27.—Four-faced Cube.

corner; this was found above to be the form resulting from the cleavage of fluor.

(2) **Dodecahedron.** Fig. 8.—The form derived by truncating the twelve edges of the cube (see Fig. 23 or 25); its faces are parallel to the six diagonal planes of symmetry. This figure is properly called the "rhombic dodecahedron" to distinguish it from the "regular dodecahedron," whose faces are regular pentagons.

(3) **Four-faced Cube.** Fig. 27.—The form derived by bevelling each cube edge as in Fig. 26. The name indicates its resemblance to a cube with a low four-sided pyramid raised upon each cube face; it is also known as the tetrakis hexahedron. The figure represents a crystal of fluor-spar from St. Agnes, Cornwall.

There are still three ways in which the corner of Fig. 24 may be modified. The octahedron face is perpendicular to three of the symmetry planes, namely, 4, 6, 8; the dodecahedron face D of Fig. 25 is perpendicular to the symmetry planes 1 and 4; the two bevelling faces T of Fig. 26 are perpendicular to the symmetry plane 1. Now a face can only be repeated over those symmetry planes to which it is not perpendicular, since over a perpendicular symmetry plane it will coincide with its own reflection; but by varying the inclination of the secondary face the following three forms are possible—

(4) **Three-faced Octahedron.** Fig. 30.—If the cube corner be replaced by a face perpendicular to the symmetry plane 8, so that it is inclined equally to the cube faces A and B, but is more nearly perpendicular to the cube face C (Fig. 28), it must be repeated over the symmetry planes 4 and 6, and will therefore be accompanied by two other faces, one perpendicular to 6, and one perpendicular to 4. Each cube corner is thus replaced by a group of three faces, as in Fig. 29; the twenty-four faces thus obtained, when extended so as to obliterate the original cube, constitute the form of Fig. 30, called the three-faced (or triakis) octahedron

on account of its resemblance to an octahedron having a low three-sided pyramid raised on each octahedron face. The figure represents a rare variety of fluor-spar from Striegau in Silesia.

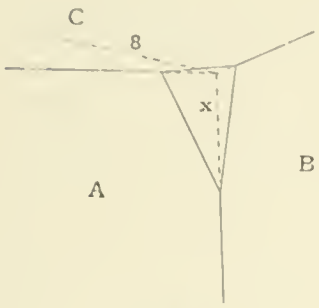


Fig. 28.

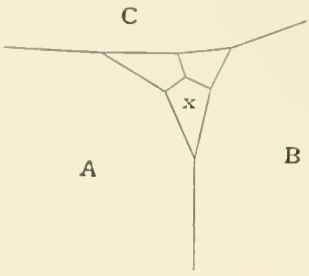


Fig. 29.

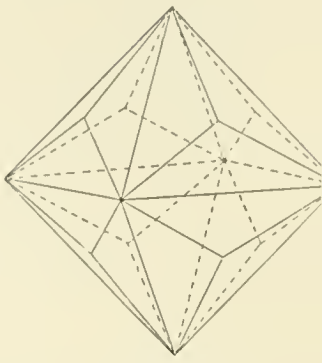


Fig. 30.
Three-faced Octahedron.

(5) **Icositetrahedron.** Fig. 33.—If the cube corner be next replaced by a face perpendicular to the symmetry plane 8, but one which is more nearly perpendicular to the cube faces A and B than it is to C, as shown in Fig. 31, this face must be accompanied by two similar faces perpendicular to the symmetry planes 4 and 6 respectively (Fig. 32); the modification of each cube corner by a similar group of three faces will

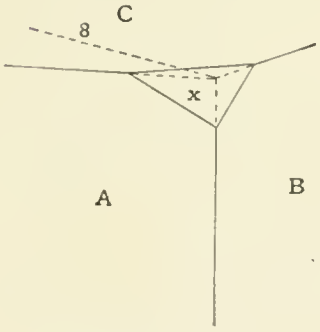


Fig. 31.

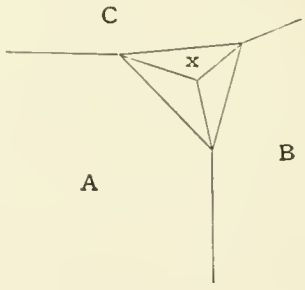


Fig. 32.

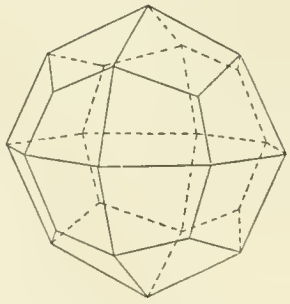


Fig. 33.—Icositetrahedron.

give rise to the form of Fig. 33, which is known as the 24-faced figure or icositetrahedron. The figure represents a crystal of analcite.

(6) **Six-faced Octahedron.** Fig. 36.—Finally, if the corner be replaced by a face x, Fig. 34, unequally inclined to the three cube faces, and therefore not perpendicular to any of the three symmetry planes 4, 6, 8, it must be repeated over these planes of symmetry and gives rise to six faces, as in Fig. 35. This group repeated over the three symmetry planes 1, 2, 3, so as to be developed on all the remaining cube corners, constitutes the form of Fig. 36, known as the six-faced (or hexakis) octahedron on account of its resemblance to an octahedron having a low six-sided pyramid raised upon each of its faces. This figure represents a rare variety of fluor-spar from Striegau.

The above are all the varieties of forms which can be symmetrically derived from the cube; any crystal of a mineral such as fluor-spar, which

is known to occur in completely symmetrical cubes, must be either one of these simple forms, or a combination of two or more of them.

About the beginning of the last century the various forms derived from the primitive figures then known were very fully described by Romé

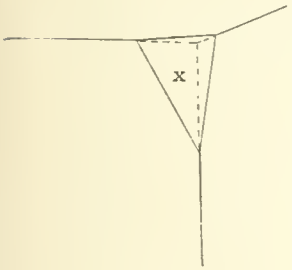


Fig. 34.

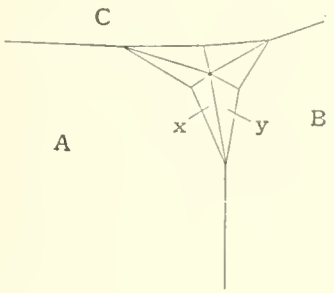


Fig. 35.

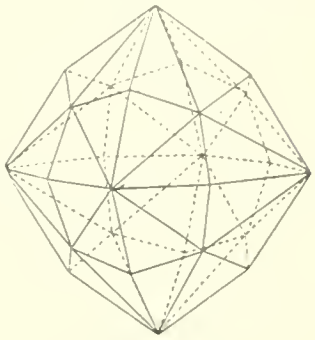


Fig. 36.
Six-faced Octahedron.

de l'Isle and by Haüy. The cube and its six derived figures were known and classed together; other crystals were classified according to the primitive figure from which they could be derived.

10. **Crystal-axes.**—Haüy imagined crystals to be constructed of minute particles having the form of the cleavage figure, and suggested a mechanical explanation of the secondary faces; according to his view they could be regarded as due to the omission or suppression of a certain number of particles along certain directions.

Thus in galena the cleavage kernel is a cube: a crystal of galena is therefore composed of minute cubic particles ranged side by side. Suppose that during the growth of the crystal a certain number of these

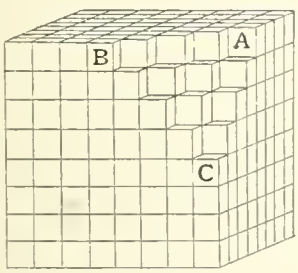


Fig. 37.

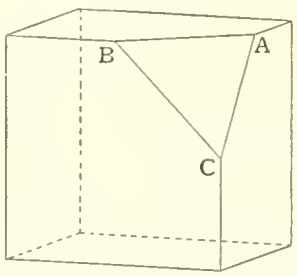


Fig. 38.

Haüy's representation of Secondary Faces.

particles be omitted along the cube edge A (Fig. 37), and the same number along the edges B, C, the result is a surface made up of the particles which lie in the plane ABC. Owing to the minute size of the particles this surface will appear smooth. We have only to suppose that the faces of a crystal are necessarily planes, and in this instance the surface is the octahedron face (Fig. 38). Other faces can be derived in a similar manner by the omission of *unequal* numbers of particles along the edges; and the derivation of all secondary forms will then be equivalent to the cutting away by new planes of certain lengths measured on the edges of the primitive figures.

The manner in which a "dog-tooth" crystal of calcite can be built up from the cleavage rhombohedron is shown in Fig. 39, which is copied from a treatise of Bergmann published in 1780. Fig. 40 is the appearance presented by Fig. 39 when the constituent particles become sufficiently small.

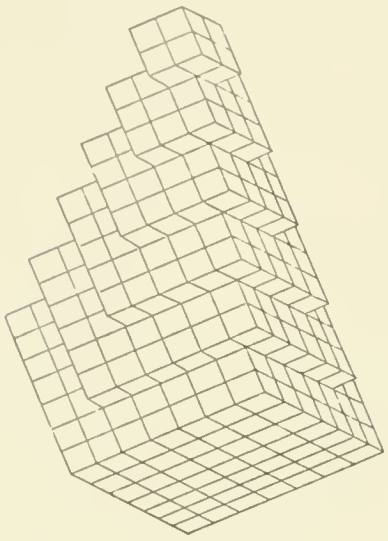


Fig. 39.

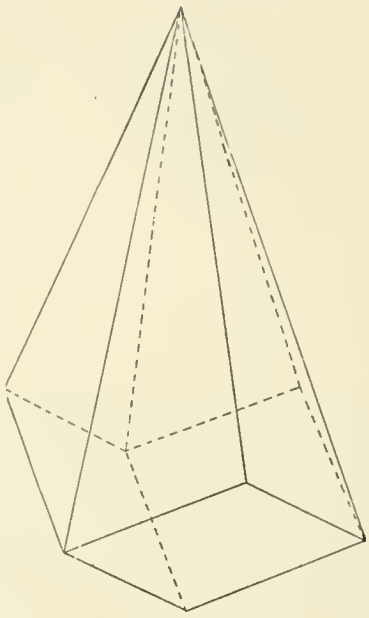


Fig. 40.

Now let OA, OB, OC (Fig. 41) be the three edges of a cube which meet in the corner O. If, according to the method of Haüy, a length OH be cut off by some face along the edge OA, then the same lengths must be cut off by the same or similar faces along the similar edges OB, OC. The octahedron face is obtained by taking three equal lengths along the three edges.

One plane of the three-faced octahedron of Fig. 30 is obtained by taking a certain length or intercept along the edge OC (see Fig. 28), and two intercepts less than this, but equal to one another, along the edges OA, OB; the remaining planes are derived by repeating the process for each of the three edges. One plane of the icositetrahedron of Fig. 33 is obtained by taking a certain intercept along one edge OC, and two intercepts greater than this but equal to each other along the edges OA, OB (Fig. 31). One plane of the six-faced octahedron of Fig. 36 is obtained by taking three unequal intercepts along the three edges. If, for example, the intercepts of the face x in Fig. 35 have the relative lengths 1 : 2 : 3 along the edges taken in the order OA, OB, OC, then, since the three edges are identical, there must also be a face y making intercepts in the ratio 2 : 1 : 3; the edges OB, OA are intersected by y at the same distances as OA, OB, respectively by x. Treating

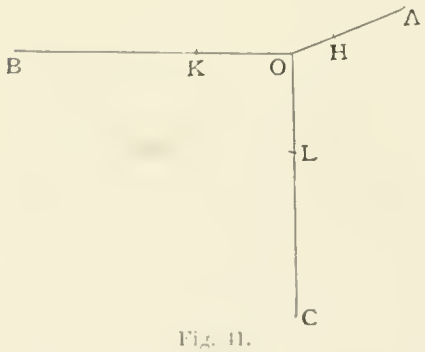


Fig. 41.

all the three edges in this way we should obtain all the six faces shown in Fig. 35, and they are the same as those obtained above by repeating one face over the three planes of symmetry.

This method of treating the secondary faces has further the advantage of suggesting a notation by which the different faces may be distinguished, for the expression 3 : 2 : 1 might now be used to denote that particular face which has intercepts in the ratio 3 : 2 : 1, upon the three edges taken in the order OA, OB, OC.

In geometry, any plane has its direction completely defined when it is referred to three known fixed lines by means of the intercepts which it makes upon them, or by means of their ratios; the direction of any face associated with the cube is completely defined by the ratio of its intercepts OH, OK, OL, upon three edges of the cube. The actual magnitudes of the intercepts are not required to be known, for a decrease or increase of their lengths, so long as their ratios are kept the same, merely corresponds to a shifting of the plane either towards or from the corner of the cube without alteration of its direction; 2 : 2 : 2 would represent an octahedron face equally inclined to the cube faces and parallel to 1 : 1 : 1; a doubling of the intercepts merely corresponds to cutting away a larger portion of the corner by a face parallel to 1 : 1 : 1.

The complete six-faced octahedron is obtained by treating all the eight cube corners in the same way as the one corner of Fig. 35. It will be necessary then, in order to denote any particular face, not only to state the ratios of its intercepts, but also to indicate the corner to which it belongs.

Since the cube edges are parallel at all the corners, the process of derivation is simplified and made more symmetrical by transferring the three lines of reference from the corners to the centre of the cube, extending each line in both directions and distinguishing its ends as positive and negative.

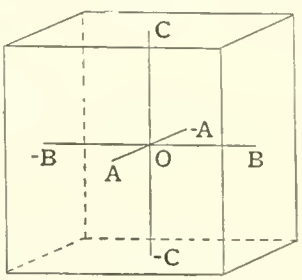


Fig. 42.

The three lines so placed are called the three "Axes" (see Fig. 42), and the position of any face upon the crystal is defined by the ratio of its intercepts upon the three axes, which are always taken in the same order, namely, OA, OB, OC.

Thus the octahedron face upon the upper left-hand front corner of the cube might be denoted by 1 : − 1 : 1, since a face parallel to it would pass through A, − B, C; an octahedron face passing through − A, B, − C might be denoted by − 1 : 1 : − 1. The axes used here are the intersections of the three cube planes of symmetry, and are more symmetrically placed in a cubic crystal than any other three lines of reference (such, for instance, as three edges of the octahedron); for this reason, as will be seen below, the axes of crystals are always chosen from the intersections of their planes of symmetry where this is practicable.

When a face is parallel to one of the axes, as is, for instance, the

dodecahedron face D of Fig. 25, the corresponding intercept may be called ∞, and the face might be denoted by the symbol $\infty : 1 : 1$.

Now, in the cube the three axes are equal in length, but some minerals cannot be referred to three *equal* axes. The primitive form of anhydrite consists, like the cube, of six faces at right angles to each other; since, however, there is a perfect cleavage parallel to the side faces, a less perfect cleavage parallel to the front and back faces, and a still less perfect cleavage parallel to the top and bottom faces, these three pairs of planes cannot be similar. Hence, also, their three edges are not in reality similar, but consist of three different sets which are to be distinguished, and in a model or figure would be geometrically represented by three unequal lines.

The three axes of the cube were found to be equal, because equal intercepts were made upon them by the octahedron face; in the same way the relative lengths of the three axes of anhydrite must be found from the three intercepts made upon them by some secondary face which replaces the corner of its primitive figure. Crystals of anhydrite from Aussee in Styria are found to have their corners replaced by such faces (*x*, Fig. 43). But the intercepts which these faces make on the three edges are not equal. From the angles at which the face *x* is inclined to the edges or faces of the primitive figure it is possible to calculate its intercepts on the axes; and it is found that in anhydrite the intercepts

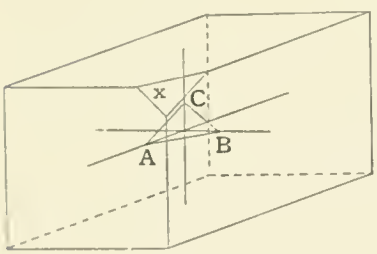


Fig. 43.

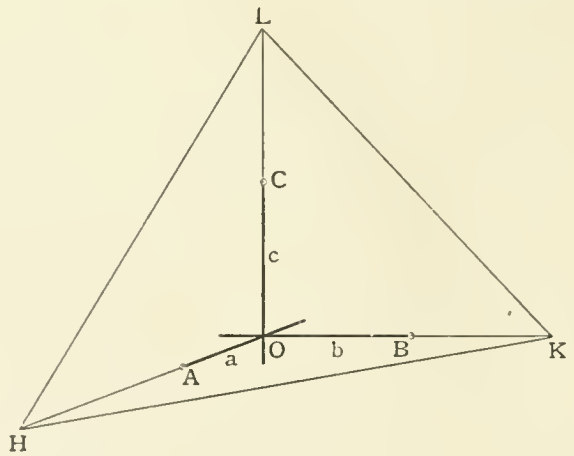


Fig. 44.

may be represented by the three numbers 893, 1000, 1001, taken in the order OA, OB, OC, so that they are not quite equal. The three axes of anhydrite are therefore taken in these proportions.

If now these three lengths be denoted by the letters a, b, c, any other face on the crystal may have its position and direction defined by the intercepts which it makes upon the axes, and may be denoted by a symbol $ma : nb : rc$, in which these three quantities give the ratios of its intercepts. Thus a face which has intercepts in the ratios $OH = 3OA = 3a$; $OK = 2OB = 2b$; $OL = 2OC = 2c$ (Fig. 44), may be denoted by the symbol $3a : 2b : 2c$. The use of axes was first introduced by Weiss of Berlin in 1818, and the above notation was employed by him.

The lengths of the axes are often called the **parameters**, and the face used to determine these lengths is called the **parametral face**.

In a cubic mineral the octahedron is the parametral form; in the case of anhydrite the face having the intercepts 893, 1000, 1001, has been chosen as parametral face.

11. **Law of Rational Intercepts.**—According to Haüy's theory any face is a plane passing through a number of the small cleavage particles of which the crystal is constructed.

Now take a mineral such as galena, whose cleavage is parallel to the cube faces. A cube of galena is supposed to consist of minute cubes ranged side by side, as shown in Fig. 37. Consider a face replacing the cube corner; it must pass through certain particles on the cube edges; suppose it to pass through the eighth on OA, the sixth on OB, and the fourth on OC. The three intercepts will then be in the ratio of 4 : 3 : 2. (In Weiss's notation the face would be $4a : 3a : 2a$.)

If Haüy's theory of crystal structure be true it is clear that whatever the intercepts may be they must always be in the ratio of whole numbers, since they are obtained by removing a certain number of particles along each edge. From these considerations we are led to enunciate the "law of rational intercepts," according to which—

The intercepts made on the crystal-axes by any face of the crystal must be such that they can be expressed as rational multiples of the parameters.

Haüy's own observations and those of subsequent workers have only tended to confirm the truth of this remarkable law, which is universally recognised at the present time as the geometrical basis of crystallography; and indeed without some such law the growth of crystals would present hopeless complexity, for there would be no limit to the number of forms possible.

Without necessarily accepting Haüy's theory of crystal structure we can adopt the law of rational intercepts as a statement of observed facts.

Expressed in Weiss's notation the symbol of any face being $ma : nb : rc$ (in cubic crystals, where the axes are equal, it is $ma : na : ra$), then according to the law of rational intercepts the numbers m, n, r, are not absolutely arbitrary, but must be whole numbers.

For instance, in the three-faced octahedron of Figs. 30 and 46 it was said that the form is constructed by taking a certain intercept on one axis, and two equal but less intercepts on the other two axes; no limit was there placed upon the values of these intercepts; it might appear that an infinite number of three-faced octahedra is possible, having any ratios, such for instance as $\sqrt{2} : \sqrt{2} : 3$ or $\sqrt{3} : \sqrt{3} : 2$. But from the law of rational intercepts it now appears that these can only be whole numbers, such as 2 : 2 : 3 or 3 : 3 : 4.

Fortunately, moreover, it is found that the faces of common occurrence in nature are only those whose intercepts have very simple ratios, so that the numbers m, n, r, are almost always *simple whole numbers*, rarely

greater than 5 or 6 ; this fact makes the study of crystals comparatively simple.

12. Indices.—The notation of Weiss has now been entirely superseded by a more convenient notation, which (though first employed by Whewell) is commonly known by the name of the Millerian system, in consequence of its use by Miller of Cambridge in his remarkable works on Crystallography and Mineralogy.

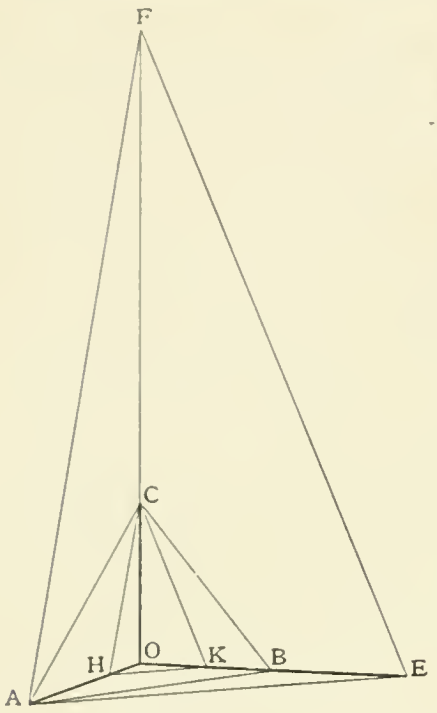


Fig. 45.

Let ABC in Fig. 45 represent the face whose intercepts are a, b, c, in a crystal of which OA, OB, OC, are the axes ; then AEF may be a second face in which the intercepts are $OA = a$, $OE = 2OB = 2b$; $OF = 4OC = 4c$.

In the Millerian system we imagine the face shifted towards the centre O, without any change of its direction, until it passes through C, and occupies the position HKC, so that it no longer lies outside the extremities ABC of the parameters. Its intercepts are now $OH = \frac{1}{4}a$, $OK = \frac{1}{2}b$, $OC = c$; the process has been equivalent to dividing the previous intercepts by 4.

From these intercepts $\frac{a}{4}, \frac{b}{2}, \frac{c}{1}$, the sign (421) is used in the Millerian notation as the symbol of the face, and the three numbers 4, 2, 1, are called its "**indices.**"

Generally, let the axes of a crystal be the three lengths a, b, c, then the symbol of any face is (h, k, l), where h, k, l, are three numbers such that the intercepts made upon the axes are

$$\frac{a}{h}, \frac{b}{k}, \frac{c}{l}$$

In the cube the three axes are equal and may be called a, a, a.

The intercepts of the octahedron are $\frac{a}{1}, \frac{a}{1}, \frac{a}{1}$, and its symbol is (111).

The intercepts of the dodecahedron face D of Fig. 25 are ∞a, a, a, or $a, \frac{a}{1}, \frac{a}{1}$, and its symbol is (011).

The intercepts of the lowest face of the three-faced octahedron of Fig. 46 may be a, a, $2a$, or $\frac{a}{2}, \frac{a}{2}, \frac{a}{1}$, and its symbol is then (221).

Intercepts measured in the negative directions are indicated by corresponding indices having a negative sign placed over them.

Fig. 46 shows the indices of the faces in a complete three-faced octahedron.

When the axes are chosen symmetrically the faces which constitute a "form" generally have the same three numbers for their indices, and are only distinguished by the order and signs of these numbers, all the faces of Fig. 46, for instance, have symbols composed of the numbers 2, 2, 1.

The symbol of a form is denoted by enclosing the symbol of any one of its faces in a twisted bracket. Thus the symbol of the complete three-faced octahedron of Fig. 46 is $\{221\}$, this being understood to signify the whole group of faces, which must be developed together by virtue of the symmetry of the cube.

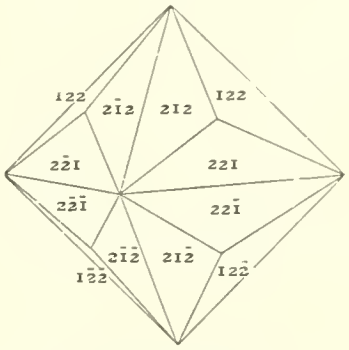


Fig. 46.—Form $\{221\}$.

The axes are not even necessarily at right angles to each other; it is only necessary that they be chosen parallel to three edges of the crystal.

Thus, if OA = a, OB = b, OC = c (Fig. 48) are the lengths of the axes in the oblique-shaped crystal of Fig. 47, these lengths being determined by the intercepts made upon them by some face of the crystal which has been selected as parametral plane, then any face x (or HKL, which is parallel to it) has the symbol (hkl), where $\mathrm{OH} = \frac{a}{h}$, $\mathrm{OK} = \frac{b}{k}$, $\mathrm{OL} = \frac{c}{l}$.

The use of indices is at first somewhat confusing on account of their representing fractional values of the intercepts; it must always be borne in mind that the greater the index, the less is the corresponding intercept;

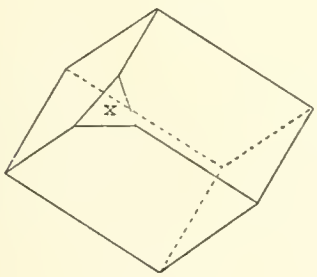


Fig. 47.

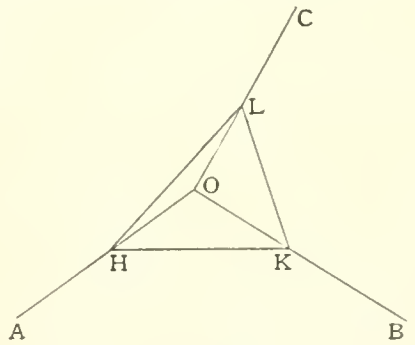


Fig. 48.

in the face (321), for example, the intercept on the first axis is the least, and that on the third axis the greatest; the index 0 always indicates that the face is parallel to the corresponding axis.

13. **Law of Rational Indices.**—In the Millerian notation the "law of rational intercepts" becomes the "law of rational indices." For if the intercepts are ma, nb, rc, their values may be divided by the product mnr, and they become $\frac{a}{nr}$, $\frac{b}{rm}$, $\frac{c}{mn}$, so that the indices are nr, rm, mn. But m, n, and r are whole numbers, therefore these indices are also

whole numbers. In its most general form the law may be thus stated (see Fig. 18):—

Let OA, OB, OC, be the three axes parallel to the edges formed by any three faces of a crystal; let the lengths of the axes be a = OA, b = OB, c = OC, as found from the intercepts made upon them by a fourth (parametral) face on the crystal. Then if H, K, L, are the points at which the axes are intersected by a plane parallel to any other face of the crystal

$$OH = \frac{a}{h}, \qquad OK = \frac{b}{k}, \qquad OL = \frac{c}{l}$$

where h, k, l, must be whole numbers.

The ratios of the axes $a : b : c$ themselves (except in crystals derived from the cube) need not necessarily be (and are not in general) whole numbers.

It must be observed that the law of rational indices is true if *any* three edges are chosen for axes; but as was said above it is always convenient to choose axes which are the intersections of planes of symmetry in order to simplify the indices.

14. **Zones.**—A number of faces may replace an *edge* of a crystal, as in Fig. 26, so as to intersect one another in parallel edges; if a line be drawn through the crystal parallel to that edge, and therefore also to their mutual intersections, the replacing faces are of necessity parallel to that line. It is found that the faces of a crystal fall as a rule into sets which are parallel to a *few* such lines. Thus, for instance, the prism faces of the quartz crystal in Fig. 1 are parallel to a vertical line and intersect in vertical edges. A set of faces on a crystal which are all parallel to the same line, and which would therefore, if they met, intersect in parallel edges, is called a "**zone**" of faces; the line to which they are parallel (which is supposed drawn through the intersection of the axes) is called the "zone-axis."

Zones are of great importance in the study of crystals, because it is found that all the faces on any one crystal, however complicated it may be, generally belong to a very few zones. But it rarely happens that all the faces which belong to a zone actually intersect each other in parallel lines; their edges are often replaced by faces which do not belong to the zone.

15. **Projection.**—Before considering further the geometrical properties of crystals it will be necessary to describe a graphic method by which their symmetry and the position of their faces may be very conveniently represented, a method first introduced into mineralogy by Neumann in 1823.

From what has been said above it is clear that the study of crystals is occupied, not with the shapes or sizes of the faces, but only with their directions; now the perspective figures used above represent not only the positions but also the sizes of the faces; the method to be next described indicates their directions alone.

The direction of a plane is completely defined if we know that of its

normal. Let, then, any point O be chosen inside the crystal as "origin"; let the whole set of faces be replaced by their normals, that is by lines drawn perpendicular to them through the origin. Each normal now represents a face, and the direction of each is defined by the angles which it makes with the three axes. If, for example, normals be drawn to the faces of the regular octahedron they constitute a sheaf of eight lines inclined to one another at angles of 70° 31′, and to the axes at 54° 44½′ (Fig. 49). Such normals do not of course necessarily meet their corresponding faces on an actual crystal; a small facet is not always situated exactly upon its normal, but each face is regarded as a plane extended in all directions and the normal is drawn perpendicular to the plane.

Now it is possible to represent the normals themselves in a far more convenient way than by a perspective drawing. For this purpose the crystal is supposed to be surrounded by a hollow sphere having its centre at O, and the normals are prolonged to meet the sphere in points; in this way a point is found on the sphere corresponding to each face of the crystal, and is called the "**pole**" of the face. The axes of the crystal are also prolonged to meet the sphere in the points XYZ (Fig. 50).

If a series of faces belong to the same zone their normals must all lie in a single plane (called the "zone plane"), which is perpendicular to the zone axis; and since the zone plane passes through the centre of the sphere it cuts the sphere in a great circle called the "**zone circle.**" Fig. 51 shows a crystal of quartz with its prism zone and the corresponding zone circle. If the planes of symmetry be also drawn through the centre they

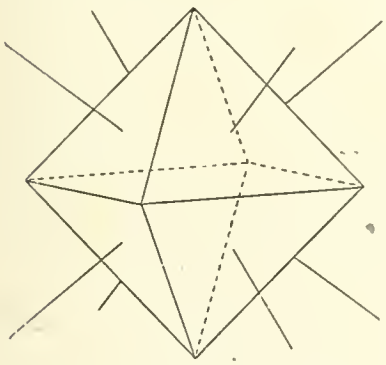


Fig. 49.—Normals of Octahedron.

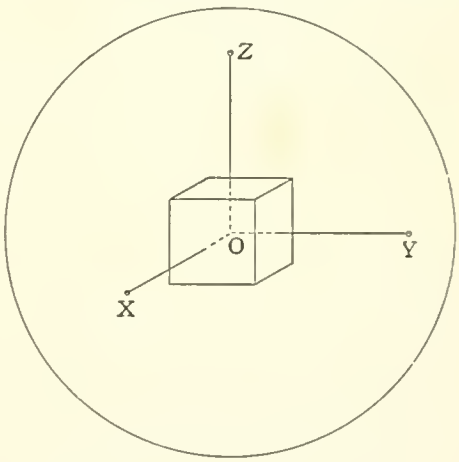


Fig. 50.—Axes intersecting sphere.

will intersect the sphere in great circles, which may be called "**symmetry circles.**"

In place, then, of the crystal we have a sphere bearing on its surface the three points (X, Y, Z) in which it meets the axes, and also a number of poles corresponding to the faces of the crystal; the poles of all the faces which belong to any one zone lie upon the corresponding zone circle. The position of any pole is then defined by its angular distances from the three points X, Y, Z, in other words by the arcs which join it to those

points; these measure, of course, the angles which the normal makes with the three axes.

If the sphere and the poles upon it were drawn in perspective, as in Fig. 51, there would not be much advantage in this method of representa-

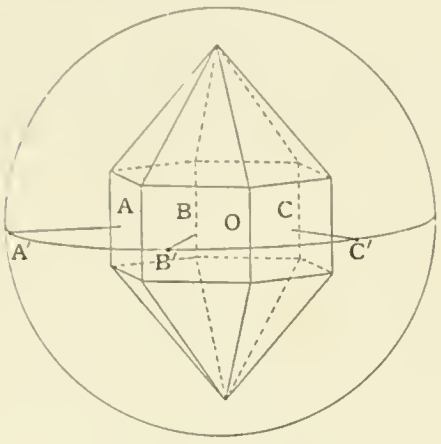


Fig. 51.—Zone-circle.

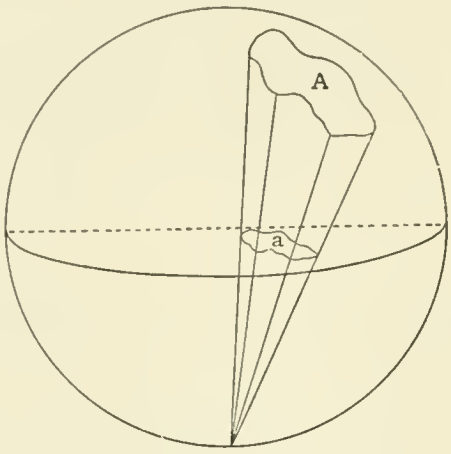


Fig. 52.—Stereographic Projection.

tion as compared with the ordinary perspective figures (5 to 50), but its value is immensely enhanced by the fact that there is a method of drawing the sphere, different from those usually adopted for maps of the globe, which is particularly convenient for the representation of crystal faces; this is known as the "**Stereographic Projection.**"

In this method the plane of the paper is taken as the plane of the equator on the sphere; crystal poles on the northern hemisphere are joined to the south pole by straight lines passing through the paper, and the points in which these lines intersect the paper constitute a picture or

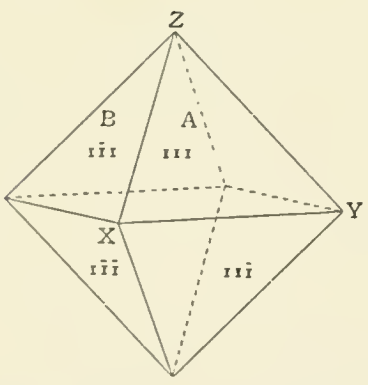


Fig. 53.—Octahedron in usual position.

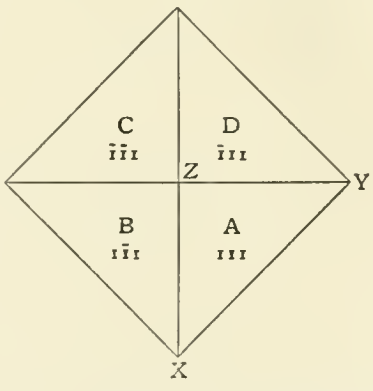


Fig. 54.—Octahedron viewed from above.

"projection" of the poles on the northern hemisphere; any figure may be projected in this manner, as shown in Fig. 52, where each point on the figure *a* is the projection of a corresponding point of the figure A drawn on the sphere. The whole figure *a* lies within the circle of the equator.

The peculiar advantage of this "stereographic" projection is that all

circles on the sphere become circles or straight lines in the plane figure, and not ellipses, so that they are easily drawn with compasses and ruler.

If the plane of the paper be taken as the equatorial plane the summit of the crystal is usually taken as the north pole, and therefore occupies the centre of the equatorial circle, the crystal being viewed from above. Thus Fig. 55 is the projection of the upper half of the regular octahedron (Fig. 53), which is first turned over into the position of Fig. 54, and then projected.

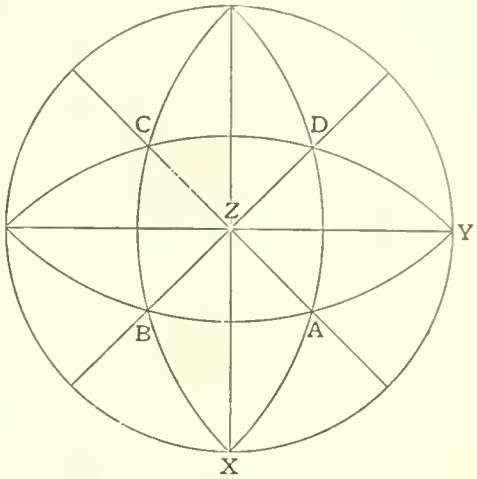


Fig. 55.—Projection of Octahedron.

The lines and circles in Fig. 55 are the intersections of the sphere with the planes of symmetry of the octahedron.

Poles which belong to the lower half of the crystal may be represented by circlets; their position is given by straight lines joining points on the *southern* hemisphere to the *north* pole. When the equatorial plane is a plane of symmetry these will exactly coincide with the poles belonging to the upper half of the crystal, since the northern and southern hemispheres are then identical (see Fig. 95).

16. **Angle between Crystal Faces.**—The angle between two faces of a crystal is always measured by the angle between their normals. Thus the angle between the two faces AB is the angle α which is enclosed between their normals (Fig. 56), and not β, which is the plane angle of a section through the faces perpendicular to their edge; the latter is what is commonly understood by the angle between two planes, except in crystallography, and was the angle used by crystallographers from the time of Steno until the introduction of the use of face normals and their projections.

These two—α the normal angle, and β the internal angle—are connected by the very simple relation $\alpha + \beta = 180°$.

The use of the normal angle in crystallography is very convenient for two reasons: it is the angle actually measured by the reflecting goniometer (see p. 101); and it is the arc distance between the two poles on the sphere of projection.

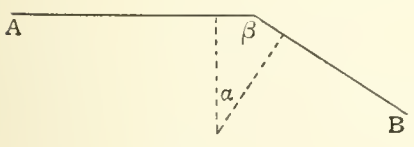


Fig. 56.

Whenever the angle between two crystal faces is mentioned in this book it must be understood to mean the angle between their normals; thus the angle between two faces is very small when they nearly coincide, and is 180° when they are opposite to one another and parallel.

17. **Use of Symbols.**—Since the indices by their values denote the ratios of the intercepts upon the three axes, and therefore implicitly also the inclinations of the face to the axes, there must be a simple relation

connecting the indices with these inclinations. The relation is as follows:—

Let P (Fig. 57) be the pole of a face whose indices are (hkl), and let XYZ be the points in which the axes meet the sphere, then

$$\frac{a}{h}\cos \mathrm{PX} = \frac{b}{k}\cos \mathrm{PY} = \frac{c}{l}\cos \mathrm{PZ}.$$

Here the arc PX is the angle included between the axis OX and the normal to P; PY and PZ having similar significations.

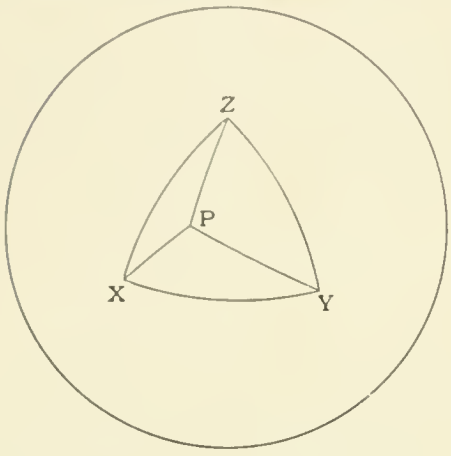


Fig. 57.

These equations are the basis of all the relations which have been discovered between the angles and the indices of crystal faces; and the relations having once been established, all the problems of crystal calculation resolve themselves into simple problems of spherical trigonometry.

It will be sufficient here to indicate how the projection gives in a very simple manner not only the interfacial angles of a crystal but also the plane angles, and therefore the shapes, of its faces. If ABC (Fig. 59) be the poles of the three faces ABC (Fig. 58), then all their angular relations are given by the spherical triangle ABC, for its three sides AB, BC, CA, are the angles between those faces as measured by the goniometer. The angle α at A is the angle between

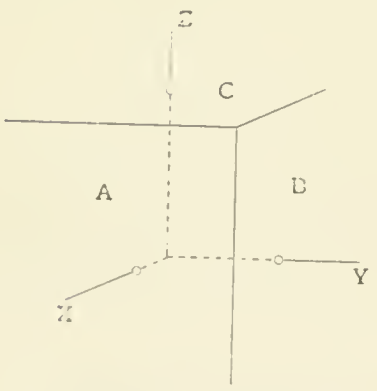


Fig. 58.—Axial Planes.

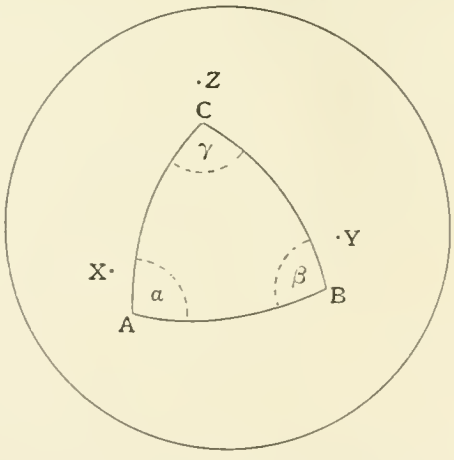


Fig. 59.—Projection of Axial Planes and Zones.

the zone CA and the zone AB, *i.e.* between the edge Y and the edge Z; thus the three angles α, β, γ, are the plane angles of the faces; and these plane angles may be deduced from the interfacial angles by means of the formulæ which connect the sides and angles of a spherical triangle.

If ABC are the three planes chosen for the primitive figure, their

intersections being taken as the axes, the points X, Y, Z, do not necessarily coincide with the poles of A, B, C. In fact OX, the axis a, being parallel to the faces B and C, must be perpendicular to their normals, and therefore X in the projection is a pole of which the circle BC is the equator; similarly Y is the pole of the circle CA, and Z is the pole of AB.

In some crystals, such as those derived from the cube, X, Y, Z do coincide with A, B, C, for in the cube the axes are perpendicular to the faces.

In any case, if A, B, C, are the "axial" planes, their symbols must be A = (100), B = (010), C = (001).

The following are a few of the more important applications of symbols.

18. **Zone Symbol.**—Any two faces which are not parallel determine a zone; let their symbols be (hkl) and (pqr); then the "symbol of the zone" is said to be $[uvw]$ where

$$u = kr - lq\,; \quad v = lp - hr\,; \quad w = hq - kp.$$

The three numbers uvw are found by writing the symbols of the two faces one below the other, thus :—

$$\begin{array}{cccccc} h & k & l & h & k & l \\ & \times & \times & \times & & \\ p & q & r & p & q & r \end{array}$$

and multiplying in the manner indicated by the cross-strokes, beginning with the second index; thus $u = (k \times r) - (l \times q)$, etc.

This process is called "cross-multiplication," and the symbol of a zone is said to be found by cross-multiplying the symbols of two faces belonging to it. The same symbol will be obtained for the zone whatever pair of faces be selected, provided that they are in that zone.

Example.—The symbol of the zone containing the two faces (111) and $(11\bar{1})$ is $[\bar{1}10]$ for :—

$$\begin{array}{cccccc} 1 & 1 & 1 & 1 & 1 & 1 \\ & \times & \times & \times & & \\ 1 & 1 & \bar{1} & 1 & 1 & \bar{1} \end{array} = [(1 \times \bar{1}) - (1 \times 1),\ (1 \times 1) - (1 \times 1),\ (1 \times 1) - (1 \times 1)]$$

$$= [\bar{2}20] = [\bar{1}10].$$

A zone symbol, like the symbol of a face, remains the symbol of the same zone when its indices are all multiplied or divided by any number, or when all their signs are changed.

The symbol of a zone is always enclosed in square brackets to distinguish it from the symbol of a face or of a form. It is to be observed that the three numbers in a zone-symbol have not the same meaning as the three indices in a face-symbol and must not be confused with them.

The chief uses of the zone symbol result from the three following properties.

(1) If the face (hkl) belongs to the zone $[uvw]$ then

$$hu + kv + lw = 0.$$

Thus in Fig. 53 and the projection Fig. 55, the symbol of the zone containing the two faces (111) ($1\bar{1}1$) is, as has just been shown, [$\bar{1}10$]; should it then be required to know whether the face 110 belongs to this zone, the question is at once answered in the affirmative by applying the above test, for

$$(1 \times \bar{1}) + (1 \times 1) + (0 \times 0) = 0.$$

(2) If a face belongs to two zones its symbol is found by cross-multiplying the two zone-symbols.

Example.—A face which belongs to both the zones [$\bar{1}10$] and [012] will have the symbol ($22\bar{1}$).

(3) If the symbols of two faces be added together, index by index, the result is the symbol of a face replacing their edge, that is to say, of a face whose pole lies between their poles and on the same zone circle. The same is true if any multiple of one symbol be added to any multiple of the other.

Example.—$2(12\bar{1}) + 3(232) = (8\bar{5}4)$ is the symbol of a face lying between the faces ($12\bar{1}$) and ($2\bar{3}2$) and in their zone.

This rule is of practical use in several ways, but especially in determining the sign to be given to the indices of a face which has been found by cross-multiplying two zone symbols; thus the face belonging to the two zones [110] and [012] will be found to be either ($22\bar{1}$) or ($\bar{2}2\bar{1}$), according as the first or the second zone symbol is placed first in cross-multiplying. This is because any pair of zones must meet not in one face alone but in two parallel faces whose poles are the two points in which the two zone circles intersect.

But suppose that in this instance the face in question is known to lie between (110) and ($11\bar{1}$), then it must have the symbol ($22\bar{1}$).

19. **The Zone Law.**—The relation (2) of the last article suggests another way of expressing the law of rational indices. The zone-symbol got by cross-multiplying the rational indices of two faces must itself be rational; therefore the face-symbol got by cross-multiplying the rational symbols of any two zones must also be rational. Hence all the faces obtained by constructing all possible zones on a crystal, drawing their zone circles on the projection, and taking their intersections as face-poles, must be the same as the faces obtained by taking all possible rational indices.

We may either say that all the faces of a crystal must have simple rational indices referred to its axes, or that they must lie in simple zones constructed from four of its faces.

20. **Calculation of the Axes.**—The axes of a crystal are easily deduced from a sufficient number of interfacial angles as measured by the goniometer, and in no case need this number exceed five. Thus let A, B, C, (Fig. 60) be any three faces of a crystal which are chosen as axial planes, *i.e.* the axes are to be taken parallel to their edges, and let P be the parametral plane, *i.e.* the face which by its intersections with the axes is to determine their lengths. Let XYZ of Fig. 61 be parallel to P. Then

$$\frac{a}{b} = \frac{OX}{OY} = \frac{\sin OYX}{\sin OXY}$$

from the plane triangle OYX. But OYX is the angle between the edges AC and CP lying in the plane C, *i.e.* the angle between the zones

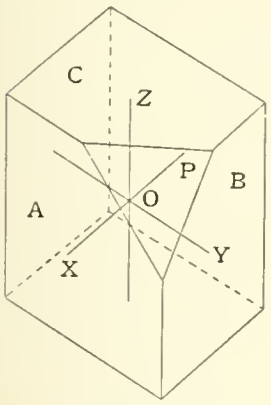


Fig. 60.

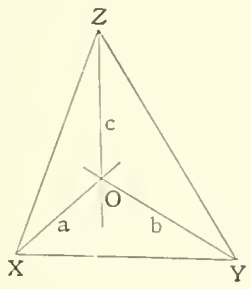


Fig. 61.

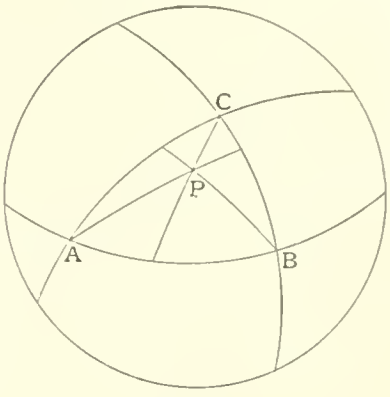


Fig. 62.

CA and CP; and OXY is the angle between the zones CB and CP. Hence in the projection (Fig. 62)

$$\frac{a}{b} = \frac{\sin PCA}{\sin PCB}.$$

Similarly

$$\frac{b}{c} = \frac{\sin PAB}{\sin PAC}$$

and

$$\frac{c}{a} = \frac{\sin PBC}{\sin PBA}.$$

These angles can be calculated from five of the measured angles AB, BC, CA, and PA, PB, PC, by solving the triangles PAB, PBC, and PCA according to the rules of spherical trigonometry.
For example

$$\cos^2 \frac{PCA}{2} = \frac{\sin s . \sin (s - PA)}{\sin PC \sin CA}$$

where

$$s = \frac{PA + AC + CP}{2}$$

with similar expressions for the remaining angles.

21. **Axes of Symmetry. Centre of Symmetry.**—All the figures derived from the cube which have been considered above are symmetrical figures, and, like the cube itself, possess the nine planes of symmetry shown in Fig. 22. Now the symmetry of a figure consists in the repetition of its parts, but this repetition may take place in other ways besides reflection over a plane of symmetry. Consider the octahedron: each of its faces would be brought into the position of the adjoining face by rotating the octahedron through 90° about the diagonal Z (Fig. 54); about any one of

its three diagonals the faces of the octahedron are therefore symmetrically distributed, so that the crystal presents the same aspect when rotated through 90°, 180°, 270°, or 360° about the diagonal.

Such a line is said to be an "axis of symmetry" to the figure, and since in this case faces are distributed in a fourfold manner about the axis, so that one quarter of a complete turn suffices to bring the crystal into a position in which its aspect is unchanged, the diagonal of the octahedron is said to be a "**tetragonal axis.**"

It will be observed also that this line is one in which four planes of symmetry intersect. A line in which four planes of symmetry intersect is called a "**ditetragonal axis.**"

Similarly it will be found that each of the four diagonals of a cube is a threefold or "**trigonal axis**" of symmetry both to the cube and to the six figures derived from it. Since three planes of symmetry intersect in this line it is called a "**ditrigonal axis.**"

In addition to tetragonal and trigonal axes two other sorts of symmetry axes are known. A "**hexagonal axis**" is one of sixfold symmetry about which the sixth of a complete turn may be made without altering the aspect of the crystal: if it is the intersection of six planes of symmetry it is called a "**dihexagonal axis.**"

A "**digonal axis**" is one of twofold symmetry about which a half turn is required to restore the aspect which the crystal presented before rotation. A "**di-digonal axis**" is the intersection of two symmetry planes.

The manner in which one face can be derived from another belonging to the same form by rotation round an axis of symmetry is most easily grasped by the repetition of one pole from another on the sphere of projection. In the projection of Fig. 55 (cf. Fig. 95), the poles of the forms are grouped in a fourfold manner about the pole (Z) where a ditetragonal axis emerges, and in a threefold manner about the pole (111) where a ditrigonal axis emerges.

Centre of Symmetry.—When each face is accompanied by a parallel face belonging to the same form, the one may be regarded as derived from the other by repetition about a centre; the crystal is then said to be "**centro-symmetrical.**" In Figs. 53-55 the derivation of any face from the parallel face (*e.g.* of $\bar{1}\bar{1}\bar{1}$ from 111) may equally well be regarded as due to a rotation of 180° about an axis of even symmetry (such as Z), combined with reflection over the plane of symmetry to which that axis is perpendicular. Rotation through 180° about the symmetry-axis Z brings (111) into the position of $(\bar{1}\bar{1}1)$, and reflection over the plane of projection brings the latter into coincidence with $(\bar{1}\bar{1}\bar{1})$. Some crystals, however, possess a centre without an axis or a plane of symmetry.

Axis of Alternating Symmetry.—In Fig. 20 every pair of adjacent faces at one end of the crystal may be regarded as derived from a similar pair at the other end by a rotation of 60° about the vertical axis followed by reflection over the horizontal plane, and yet the latter is not a plane of symmetry to the crystal. In such cases the axis is termed one of "**alternating symmetry.**" In Fig. 20 it is dihexagonal (cf. Fig. 170). In Figs. 185, 186, it is hexagonal.

22. **The Thirty-two Classes of Crystals.**—Some crystals possess only axes of symmetry; some possess only a plane of symmetry; some are only centro-symmetrical without planes or axes of symmetry; others possess more than one element of symmetry. We may next, therefore, inquire in how many ways a crystal, that is to say a figure having plane faces which obey the law of rational indices (or the zone law), can be symmetrical; how its faces may be repeated about planes, axes, or a centre of symmetry either single or combined; in other words how many types of symmetry can exist among crystals. This problem has now been solved.

In the first place it can be proved that a plane of symmetry is always parallel to a possible face of the crystal, and that an axis of symmetry is always parallel to a possible edge of the crystal. Under these conditions it may be proved (by applying the law of rational indices) that axes of symmetry must be either of 2-, 3-, 4-, or 6-fold symmetry.

By combining the three elements of symmetry in all possible consistent ways it is then found that there can only be thirty-two distinct classes. A list of these is given on p. 280.

The most symmetrical of them is the complete cubic type which has been considered above. Here the crystal has not only the nine planes of symmetry, shown in Fig. 22, but the thirteen axes of symmetry shown in Fig. 63. Each cube axis (lettered IV) is an axis of ditetragonal symmetry about which the crystal may be turned through 90° without altering its aspect. Each cube diagonal (lettered III) is an axis of ditrigonal symmetry about which the crystal may be rotated through a third of a complete turn; and each line (II) joining the centres of opposite edges is an axis of di-digonal symmetry about which the crystal may be rotated through half a complete turn without altering its aspect.

Now, since the thirty-two classes are obtained by combining in various ways the three elements of symmetry, it is not surprising that some of them are more closely allied to each other than to the remainder, and that they can be arranged into groups.

In order to bring the arrangement into harmony with a classification adopted on physical grounds, the thirty-two classes may be conveniently grouped into six "systems," according to the lengths and directions of the crystallographic axes to which they can be referred.

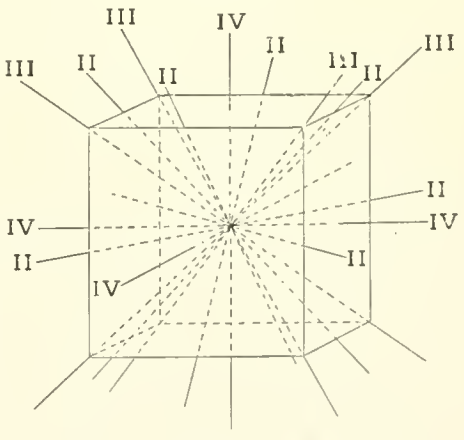


Fig. 63.—Symmetry-axes of Cube.

One must always bear in mind the distinction between the crystallographic axes (to which the indices of the faces have reference) and the symmetry-axes. The latter do not necessarily coincide with crystallographic axes. In Fig. 63 the three tetragonal axes coincide with the crystallographic axes, but the remainder do not.

Now the three crystallographic axes must either be equal or unequal;

they must either be perpendicular or inclined to each other. Since any three faces of the crystal may be chosen as axial planes to determine the directions of the crystallographic axes, and any fourth plane as parametral plane to determine their lengths, it is obvious that any crystal may, if desired, be referred to three *unequal inclined axes.*

But *for convenience* the crystal axes are always so selected as to be symmetrically placed within the crystal, and also if possible to be perpendicular to each other. For this purpose a plane of symmetry must either be perpendicular to a crystal axis or must be equally inclined to two equal axes; otherwise the axes are not symmetrical about it. Further, an axis of symmetry must either coincide with a crystal axis, or must be an axis of even symmetry bisecting the angle between two equal crystal axes, or must be an axis of three- or six-fold symmetry equally inclined to the three crystal axes; otherwise the crystal axes are not symmetrically repeated about it.

23. **The Six Systems.**—From the above considerations we may now deduce the six crystallographic systems and define the most symmetrical or "**holo-symmetric class**" belonging to each.

(1) **Anorthic.**—If the three axes are necessarily unequal and none is perpendicular to another, the crystals cannot have any higher symmetry than centro-symmetry, and are said to belong to the Anorthic system. Fig. 64

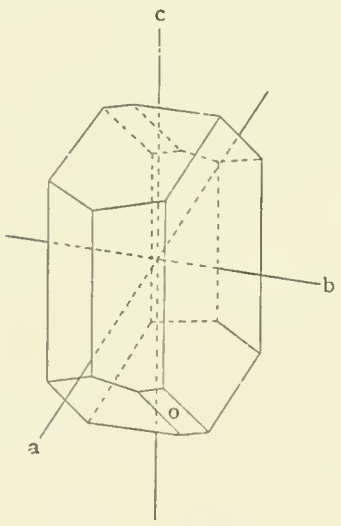


Fig. 64.—Anorthic System, Albite.

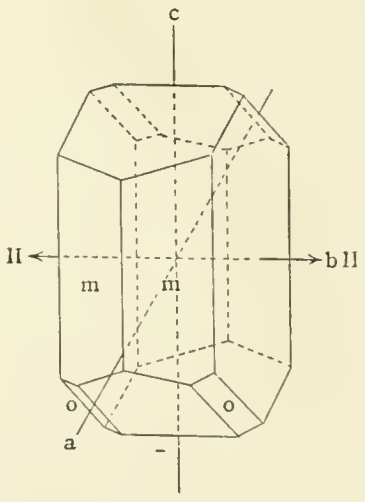


Fig. 65.—Monoclinic System, Orthoclase.

represents a crystal of albite in which the face *o*, for example, is not repeated over any plane or axis of symmetry, but only about the centre.

(2) **Monoclinic.**—If the three axes are unequal but one is perpendicular to the other two, the former may coincide with an axis of symmetry, and the two latter may lie in a plane of symmetry. Such crystals cannot have more than one plane of symmetry as in Fig. 65, and are said to belong to the Monoclinic system. In Fig. 65 the crystal axis *b* is the digonal axis, while the plane of symmetry contains the axes *ac*, and is parallel to the large face, as may be seen from the symmetrical repetition of the faces *o* and *m*.

(3) **Orthorhombic.**—If the three axes are unequal and at right angles to each other each may coincide with an axis of twofold symmetry and each pair may be in a plane of symmetry. Such crystals cannot have more planes of symmetry than those of Fig. 67, and are said to

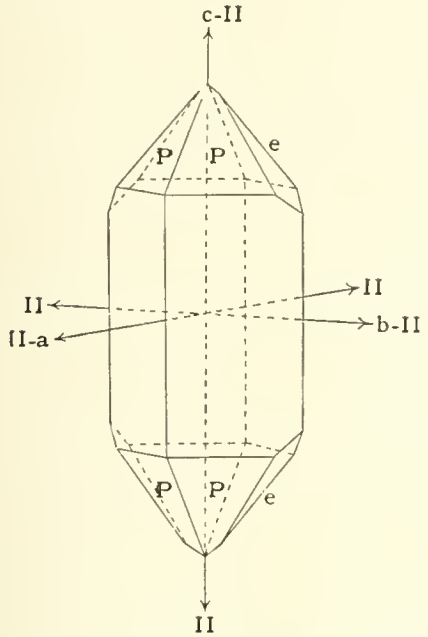


Fig. 66.—Orthorhombic System, Topaz.

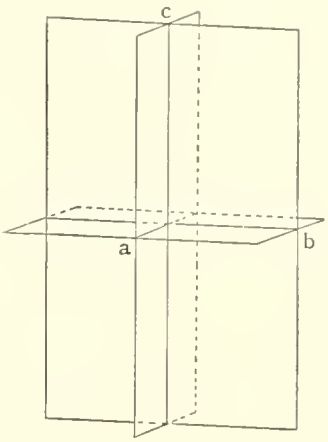


Fig. 67.—Di-digonal Axes, *a*, *b*, *c*.

belong to the Orthorhombic system. In Fig. 66 the three di-digonal axes coincide with the crystal axes *a*, *b*, *c*, and the three planes of symmetry contain these axes in pairs, as shown in Fig. 67.

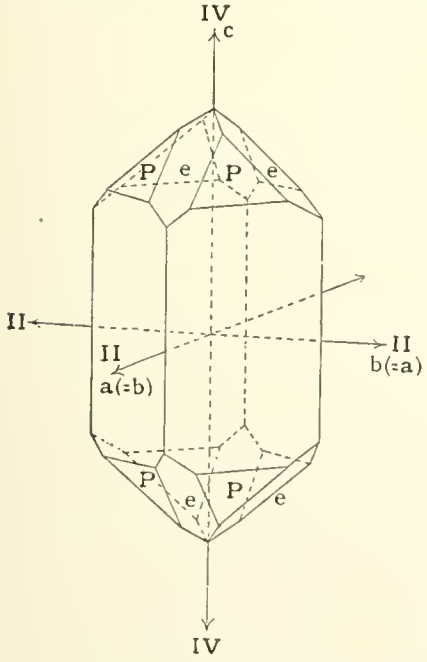


Fig. 68.—Tetragonal System, Rutile.

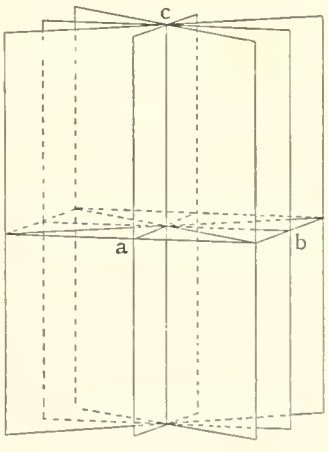


Fig. 69.—Ditetragonal Axis, *c*.

(4) **Tetragonal.**—If two of the axes are equal and at right angles to

each other and to the third, the latter may coincide with an axis of fourfold symmetry and each of the former with an axis of twofold symmetry; each pair may lie in a plane of symmetry. Such crystals cannot have more planes of symmetry than those of Fig. 69, and are said to belong to the Tetragonal system (Fig 68). The two planes of symmetry which intersect in the ditetragonal axis c contain the axes a and b; the other two bisect the angles between them (Fig. 69). The symmetry is shown by the repetition of the faces P and e.

(5) **Hexagonal.**—If the three axes are equal and not at right angles,

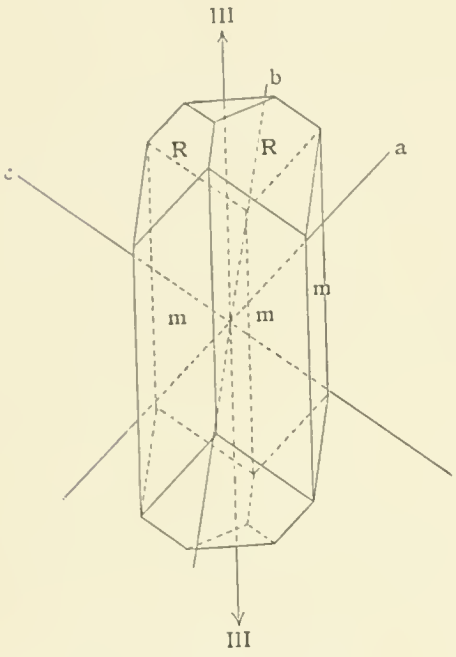


Fig. 70.—Hexagonal System.

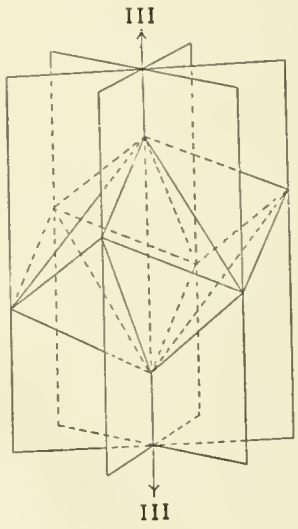


Fig. 71.—Ditrigonal Axis.

there may be an axis of threefold or sixfold symmetry equally inclined to them. Such crystals are said to belong to the Hexagonal system.

(5*a*) If the axis is one of threefold symmetry, there may further be three axes of twofold symmetry perpendicular to it and equally inclined to the crystallographic axes in pairs. Such crystals cannot have more planes of symmetry than those of Fig. 71. In Fig. 70 the digonal axes are perpendicular to the faces of the prism m; the three planes of symmetry pass through its edges (Fig. 71).

(5*b*) If the axis is one of sixfold symmetry, there may further be six axes of twofold symmetry perpendicular to it. Such crystals cannot have more planes of symmetry than those of Fig. 73. In Fig. 73 the six di-digonal axes pass through the centres and edges of the prism-faces m; of the six planes of symmetry intersecting in the dihexagonal axis each contains one of these axes.

(6) **Cubic.**—If the three axes are equal and at right angles, each may be an axis of fourfold symmetry, and there may further be four axes of threefold symmetry equally inclined to them, and six axes of twofold symmetry bisecting the angles between them. Such crystals cannot

have more planes of symmetry than those of Fig. 74, and are said to belong to the Cubic system (see Figs. 63 and 74).

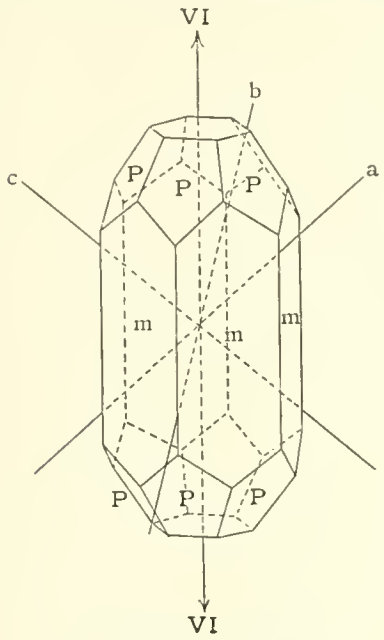


Fig. 72.—Hexagonal System.

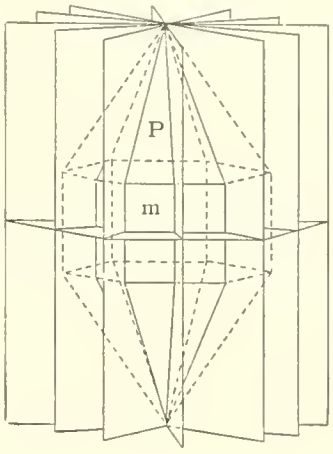


Fig. 73.—Dihexagonal Axis.

The only case which has not been considered is that in which the axes are unequal, two at right angles to each other and the third inclined to both; but it will be found on trial that such a crystal, if it exist, will possess neither planes nor axes of symmetry and would therefore belong to the first group. If two axes are equal and the third is oblique to both but equally inclined to them, the system possesses a plane of symmetry and may be referred to axes like those of the second group, to which it therefore belongs.

When an axis of symmetry is the only one of its sort in the crystal, it is called a "principal axis"; the vertical line of the figures in this book is a principal axis in the tetragonal and the hexagonal systems.

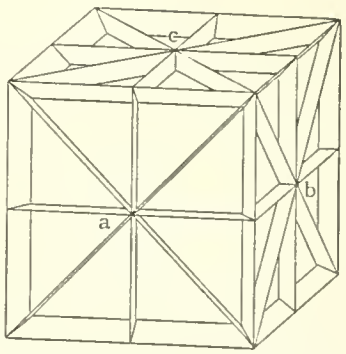


Fig. 74.—Cube with four Ditrigonal Axes (the diagonals).

Classes which belong to the same system may be recognised by two features: (1) some of their forms are identical with each other; (2) any of their forms may, by combination with other forms also having simple rational indices, present the appearance of one of the forms belonging to a more symmetrical class in the same system. These features may be illustrated by boracite.

Thus boracite crystallises in the form of the tetrahedron (Fig. 75).

This form is the figure constructed from alternate faces of the octahedron. Fig. 75 is that constructed from the shaded faces, and Fig. 77 that constructed from the unshaded faces of Fig. 76. The tetrahedron possesses no centre of symmetry, but has six planes of symmetry

passing through its edges, and also three axes of di-digonal symmetry joining the centres of its opposite edges, as shown in the figures. The latter coincide with the crystal axes, are at right angles to each other, and have equal intercepts made upon them by the tetrahedron faces. The crystal is therefore Cubic in form.

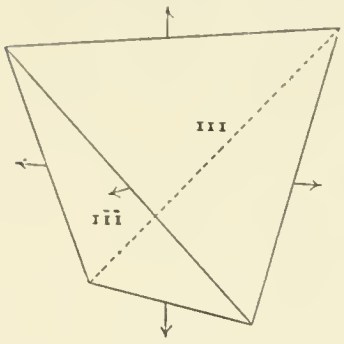


Fig. 75.

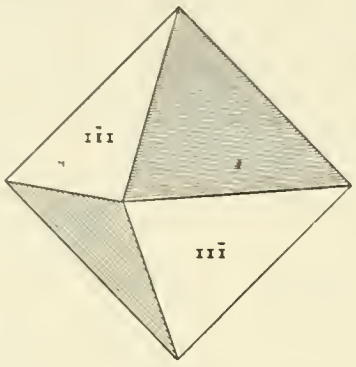


Fig. 76.

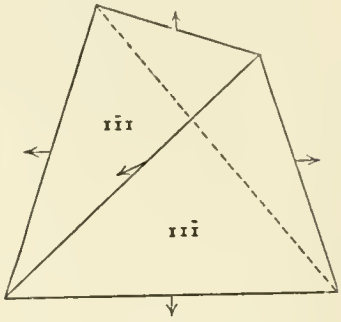


Fig. 77.

Boracite also crystallises in the combination of Fig. 78, when its edges are truncated by the six faces of the form {100}.

When these faces are more largely developed, as in Fig. 79 (also a common habit of boracite), they are easily seen to be the cube faces. Hence, whereas {111} in crystals of the boracite class is a tetrahedron instead of an octahedron, {100} is a cube just as in the holosymmetric class.

Again, boracite also crystallises in the combination of Fig. 80. This presents the appearance of the cubo-octahedron, a holosymmetric com-

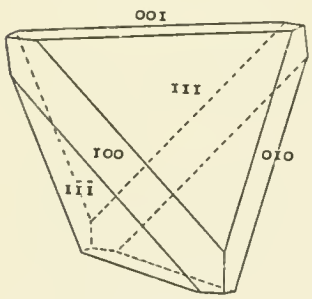


Fig. 78.

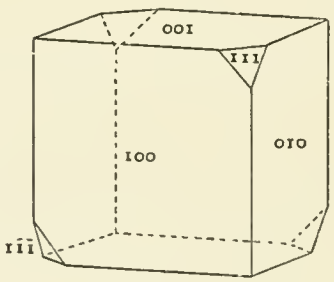


Fig. 79.

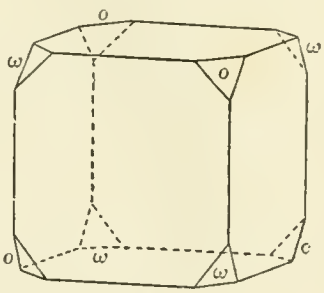


Fig. 80.

Figs. 78-80.—Boracite.

bination ; it is really a combination of three forms, namely, cube {100}, the tetrahedron *o*, {111}, and the tetrahedron ω, {1$\bar{1}$1}. Geometrically, the combination of two tetrahedra cannot be distinguished from an octahedron ; the true nature of such combinations is to be discovered from the physical characters of their faces. The natural crystal shows very clearly that *o* and ω belong to different forms, for the faces of *o* are bright and those of ω are dull.

The physical features of crystal faces not only serve to distinguish one form from another, but may also indicate the true symmetry of a single form. The fine lines or striations often found upon faces are especially useful for this purpose.

All minerals belonging to the Cubic system may crystallise in cubes, but the cubes of two such minerals may really belong to different classes and differ in their symmetry.

Thus a cube of blende striated as in Fig. 81 has only six planes of symmetry, namely, those containing opposite edges, and belongs to the

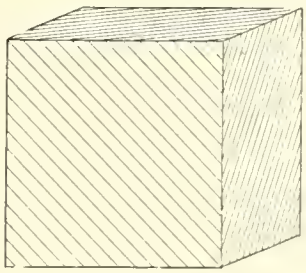


Fig. 81.

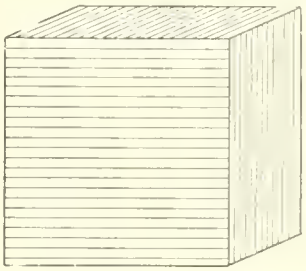


Fig. 82.

tetrahedral or boracite class just considered. But a cube of pyrites, striated as in Fig. 82, has only three planes of symmetry, namely, those parallel to its faces, and belongs to a different cubic class.

24. **Various Kinds of Forms.**—Each of the thirty-two crystal

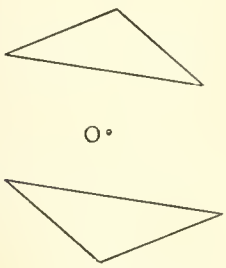


Fig. 83.—Pinakoid.

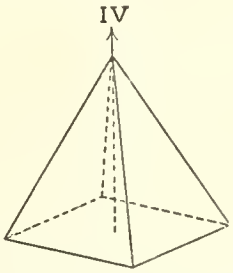


Fig. 84.—Tetragonal Pyramid.

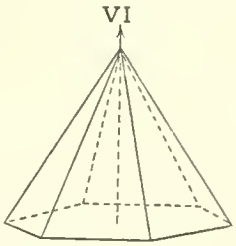


Fig. 85.—Hexagonal Pyramid.

classes may be referred to one or other of the preceding six systems. Six of the seven classes considered on pp. 38-41 possess certain features in common—each has a centre of symmetry, and every axis of n-fold symmetry is the intersection of n planes of symmetry, so that each may be taken as the most complete type of a system, and may be called "holosymmetric." Holosymmetric crystals are by many authors called "holohedral."

In the remaining twenty-five classes an axis of symmetry is not necessarily the intersection of planes of symmetry, and the crystal does not necessarily possess a centre of symmetry.

A centre of symmetry alone gives rise to a pair of parallel faces or "pinakoid" (Fig. 83). Such is the form o of Fig. 64, or, in fact, any of the forms of that figure.

An axis of symmetry alone gives rise to a "pyramid" (Figs. 84, 85).

An axis of symmetry perpendicular to a plane of symmetry gives rise to a "bipyramid" (Figs. 86, 87). Such is the form P of Fig. 72, or P of Fig. 68. When a principal axis of symmetry is perpendicular to a horizontal (or equatorial) plane of symmetry the crystal may be called "equatorial."

In Figs. 84, 85, the axis is "polar," or dissimilar at its two ends.

A plane of symmetry, alone, gives rise to a "dome," Fig. 88.

A plane of symmetry, combined with a centre of symmetry, gives rise to a "prism" (Fig. 89). Such is the form *o* or the form *m* of Fig. 65.

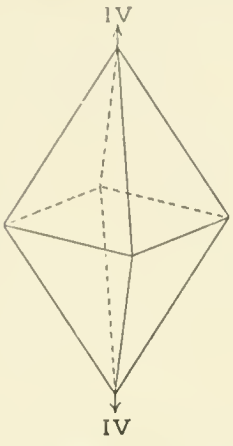


Fig. 86.—Tetragonal Bipyramid.

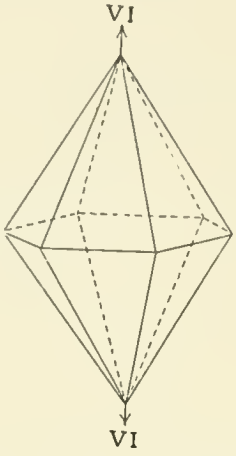


Fig. 87.—Hexagonal Bipyramid.

A ditrigonal axis in which three planes of symmetry intersect gives rise to a ditrigonal pyramid (Fig. 90).

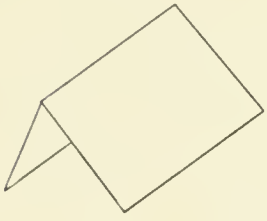


Fig. 88.—Dome.

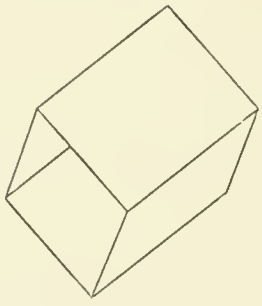


Fig. 89.—Prism.

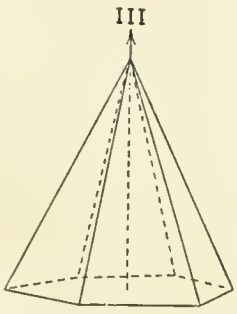


Fig. 90.—Ditrigonal Pyramid.

Similarly we may have ditetragonal and dihexagonal pyramids.

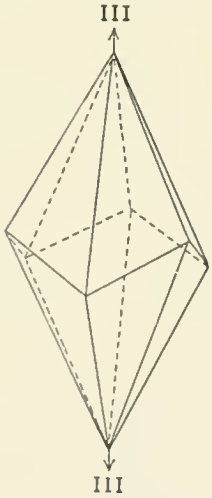


Fig. 91.—Scalenohedron.

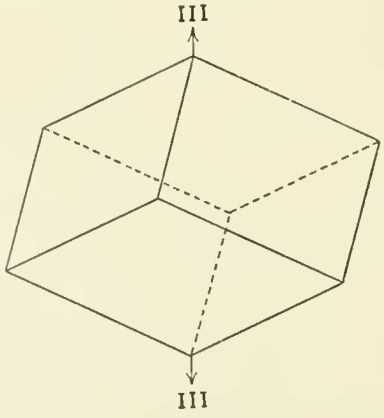


Fig. 92.—Rhombohedron.

A ditrigonal axis, combined with a centre of symmetry, gives rise to

a "scalenohedron" (Fig. 91). Such an axis may equally well be described as dihexagonal alternating.

A trigonal axis, combined with a centre of symmetry, gives rise to a "rhombohedron" (Fig. 92). Such an axis may equally well be described as hexagonal alternating.

A trigonal axis which is perpendicular to three digonal axes gives rise to a "trapezohedron" (Fig. 93).

Trapezohedra also result from a tetragonal axis perpendicular to four, and from a hexagonal axis perpendicular to six digonal axes.

When an axis of n-fold symmetry is perpendicular to n digonal axes

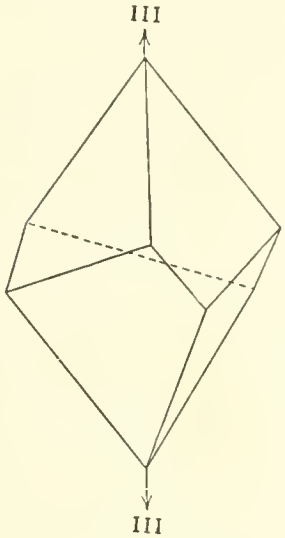


Fig. 93.—Trapezohedron.

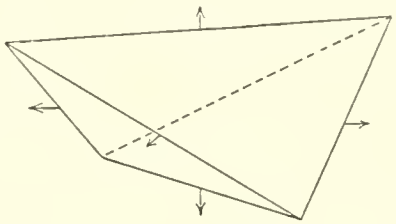


Fig. 94.—Bisphenoid.

and there is no other element of symmetry, the crystal may be called "**holoaxial**," since it possesses all the symmetry-axes compatible with each other, and only axes.

Three digonal axes at right angles to each other give rise to a "bisphenoid" (Fig. 94).

We may now consider briefly twenty-one classes which are illustrated by the crystalline forms or combinations of well-known minerals, and supply examples of central, equatorial, polar, alternating and holoaxial crystals.[1]

The Cubic System

Crystals referable to three equal rectangular crystal-axes. All crystals of this system possess four axes of threefold symmetry.

25. **Cubic System—Holosymmetric Class.**—All the holosymmetric forms have already been described, pp. 19, 20; it only remains to indicate their positions on the projection. These are easily found by considering the circles of symmetry in Fig. 95.

The four ditrigonal axes emerge at O and corresponding points; repetition about them and about the centre involves three ditetragonal

[1] In the following figures axes of symmetry are terminated by arrow-heads. On the projections, circles which are dotted are not circles of symmetry.

axes emerging at A and corresponding points; and six di-digonal axes emerging at D and corresponding points. The nine planes of symmetry have already been shown in Figs. 22, 74.

The stereographic projection of this class is divided by its circles of symmetry into forty-eight similar triangles, such as AOD, each of which has three unequal sides, namely the arcs AO, OD, DA. Now

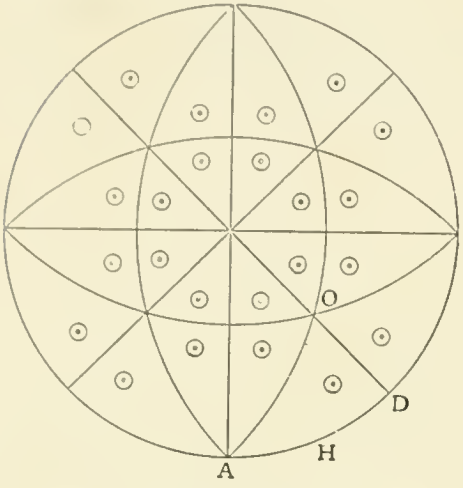


Fig. 95.—Cubic, Ditrigonal Central (Ditesseral Central).

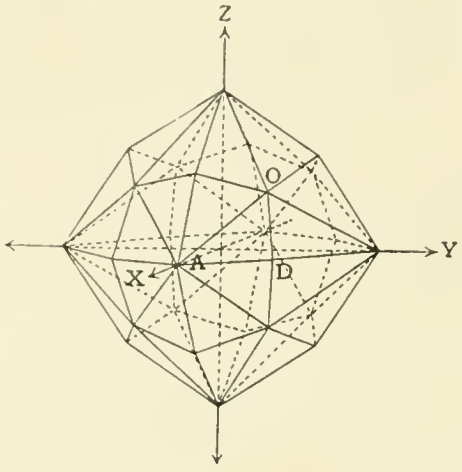


Fig. 96.—Holosymmetric Class. Six-faced Octahedron.

any pole on the sphere, whatever its position, must lie either on one of the corners, or on one of the sides, or within such a triangle; the various forms of a holosymmetric cubic crystal may therefore be deduced by supposing a pole to occupy each one of these positions in succession, and by repeating it over all the circles of symmetry. When the pole lies upon a circle of symmetry it cannot be repeated over the same, and it then represents a crystal face perpendicular to the corresponding plane of symmetry.

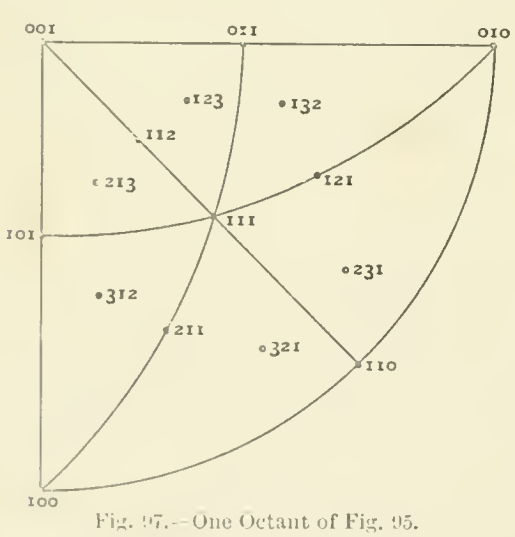


Fig. 97.—One Octant of Fig. 95.

(1) *Octahedron* {111}.—A pole situated at the corner O, if repeated over all the cube planes of symmetry, gives rise to the octahedron (Fig. 7). Spinel and magnetite crystallise in perfect octahedra.

(2) *Cube* {100}.—If the pole migrate to the corner A, the form has six faces (Fig. 6). Well-formed simple cubes are found of galena, fluor, and salt.

(3) *Rhombic Dodecahedron* {110}.—If the pole migrate to the corner D, the form has twelve faces (Fig. 8); this, the dodecahedron, is the almost universal form of garnet, and is not infrequently found as a form of magnetite.

When the pole lies upon one of the sides of the triangle, it belongs to

one of the twenty-four-faced figures; there are then three possible cases.

(4) *Three-faced Octahedron {hhk}*.—If the pole is situated between O and D the form is that of Fig. 30. A possible symbol for this figure is obtained by adding the indices of O and D, which gives {221}; the more general symbol is found by adding together any multiples of their indices. Thus m (111) + n (110) = ($m + n$, $m + n$, m) or {*hhk*} where h is greater than k. A rare form of fluor-spar from Striegau in Silesia is the three-faced octahedron {441}.

(5) *Icositetrahedron {hkk}*.—When the pole lies between O and A the form is that of Fig. 33, and the indices are usually {211}. The general symbol of any icositetrahedron must be {*hkk*} where h is greater than k, since m (111) + n (100) = ($m + n$, m, m). The icositetrahedron {211} is a common form of analcite, leucite, and garnet.

(6) *Four-faced Cube {hk0}*.—When the pole lies between A and D, as at H, it belongs to a form {*hk*0}, of which the most common instance is {210} (Fig. 27). {310} is found as a simple form in fluor-spar.

(7) *Six-faced Octahedron {hkl}*.—When the pole lies within the triangle AOD, it must be repeated over all the planes of symmetry into every other such triangle, thus giving rise to forty-eight poles, which belong to the form of Fig. 96. Any face whose indices are all unequal belongs to this form, of which {321} is a special and simple case.

The forty-eight-faced figure is scarcely known as a simple form, but some crystals of diamond *present the appearance* of a six-faced octahedron with curved faces (Fig. 419).

The accompanying diagram (Fig. 98) represents a crystal of spinel, from the Alban Mountains in Latium, which is extraordinarily rich in faces, being a combination of the forms:—octahedron O {111}, dodecahedron D {110}, cube A {100}, four-faced cube H {310}, two icositetrahedra I {311}, and *i* {611}, and the six-faced octahedron S {531}.

This combination illustrates well the fact that in a complicated crystal all the faces constitute simple zones, and have simple rational indices. The edges of the octahedron are truncated by the faces of the dodecahedron; edges of {311} are truncated by faces of {310}; and edges of {310} by faces of {611}; while {531} replaces the edge of combination between {311} and {110}, as can be seen in each case from the parallel edges in the figure, or by addition of their indices.

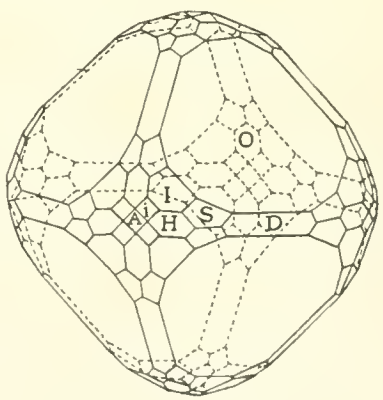


Fig. 98.—Spinel from Alban Mountains.

For examples of other holosymmetric combinations see the figures of fluor-spar (cubic habit), garnet (dodecahedral habit), galena (octahedral habit), in Part II.

26. **The Tetrahedrite Class.**—The crystals of this class possess four polar ditrigonal axes emerging at O and corresponding points, as shown

by the projection (Fig. 99): these involve three di-digonal axes emerging at A and corresponding points; the six planes of symmetry are the planes passing through the cube edges of Fig. 22.

The faces which accompany (321) by repetition about these elements of symmetry constitute the *six-faced tetrahedron* of Fig. 100, whose poles are shown in Fig. 99.

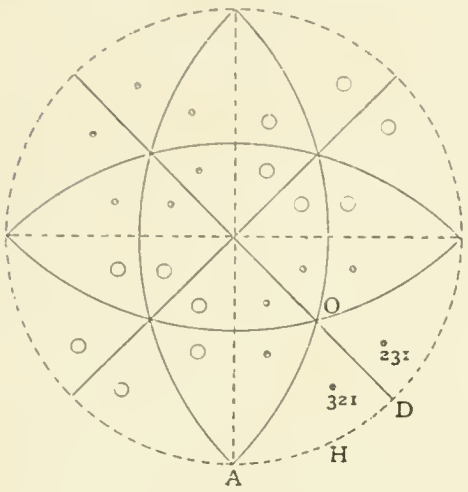


Fig. 99.—Cubic, Ditrigonal Polar (Ditesseral Polar).

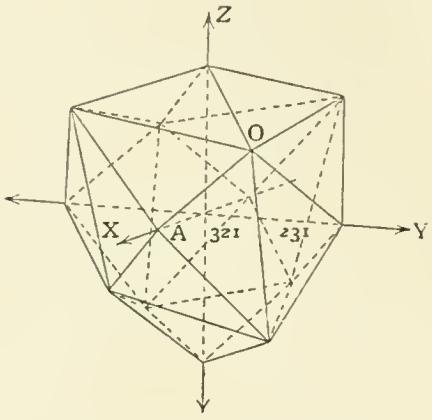


Fig. 100.—Six-faced Tetrahedron.

This figure is found, though rarely, as a simple form in diamond.

The other forms of this class are easily ascertained by imagining the pole (321) in Fig. 99 to migrate in succession to the various points of the triangle AOD, and observing how the accompanying poles must then be distributed. Thus if (321) migrate to the corner A (100), the

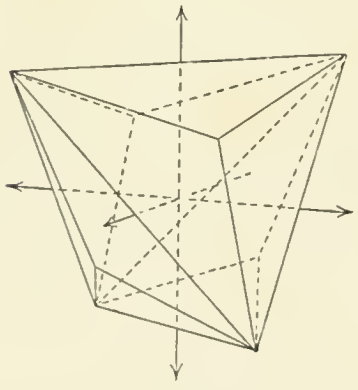


Fig. 101.—Three-faced Tetrahedron.

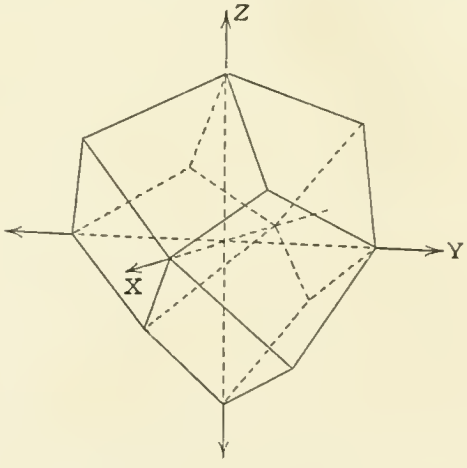


Fig. 102.—Deltoid Dodecahedron.

remaining poles of the form must simultaneously migrate to the positions of the corresponding cube poles, and *all* the six cube faces will be represented. {100} consequently retains all its faces and remains a cube in this class.

Similarly by imagining the pole to migrate to D or H it will be found that the dodecahedron and four-faced cube remain unchanged; they have

their full number of faces, and cannot be distinguished from the holosymmetric forms unless they bear superficial markings, or have physical characters, which show that they lack the planes of symmetry parallel to the faces of the cube.

On the other hand, the icositetrahedron {211} becomes the *three-faced tetrahedron* of Fig. 101; the three-faced octahedron {221} becomes the *deltoid dodecahedron* of Fig. 102, and the octahedron {111} becomes the *tetrahedron* of Fig. 103. The tetrahedron is a common form of tetrahedrite or grey copper ore; the other two figures are found in combinations. Fig. 104 represents a crystal of tetrahedrite from Dillen-

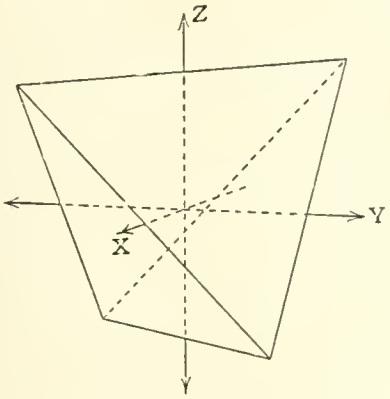


Fig. 103.—Tetrahedron.

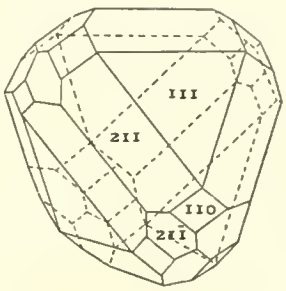


Fig. 104.—Tetrahedrite.

burg in Nassau, which is a combination of the forms :—tetrahedron {111}, dodecahedron {110}, three-faced tetrahedron {211}, and the "supplementary" three-faced tetrahedron {21$\bar{1}$}.

It will be seen that the cube truncates the edges of the tetrahedron, and that the dodecahedron forms a three-faced pyramid on each corner of the tetrahedron, and has its edges truncated by the faces of {211} and {21$\bar{1}$}. For other tetrahedral combinations see the figures of tetrahedrite, blende, boracite, and diamond.

27. **The Pyrites Class.** — The crystals of this class possess four trigonal axes emerging at O and corresponding points, and a centre of symmetry; these involve the three planes of symmetry of Fig. 105, and three di-digonal axes emerging at A and corresponding points. The faces which accompany {321} by repetition about these elements of symmetry constitute the *dyakis dodecahedron* of Fig. 106, whose poles are shown in Fig. 105. Since the figure has centrosymmetry each face has another parallel to it—and no symmetry axis is polar. Such a figure with the indices {421} or {321} is sometimes found as a simple form in iron pyrites.

Treating the other forms of the system as before, it will be found that the cube {100}, octahedron {111}, dodecahedron {110}, three-faced octahedron, and icositetrahedron are identical with corresponding forms in the holosymmetric class. On the other hand, the four-faced cube of Fig. 27 (H in Fig. 105) becomes the *pentagonal dodecahedron* {210} of

Fig. 107. This form is found in iron pyrites, and is so characteristic of that mineral that it is often known as the "pyritohedron."

Fig. 108 represents a crystal of iron pyrites from Elba, and is a

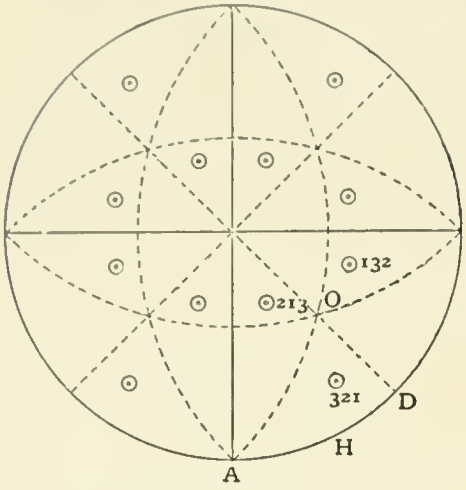


Fig. 105.—Cubic, Trigonal Central (Tesseral Central).

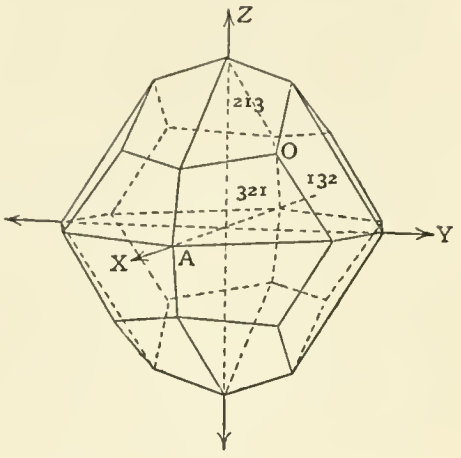


Fig. 106.—Dyakis Dodecahedron.

combination of the forms:—octahedron {111}, pentagonal dodecahedron {210}, cube {100}.

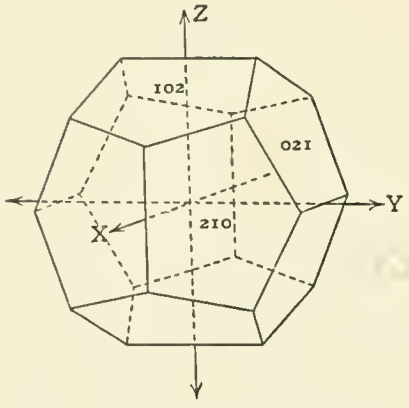


Fig. 107.—Pentagonal Dodecahedron.

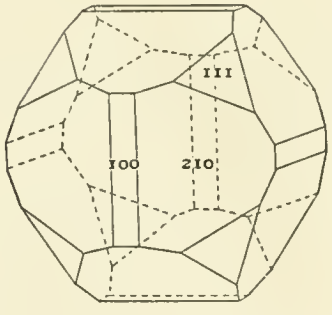


Fig. 108.—Pyrites from Elba.

28. **The Cuprite Class.** — The crystals of this class possess four trigonal axes of symmetry and are holoaxial; they have no plane of symmetry nor a centre of symmetry, but they possess all the symmetry axes possible, namely, tetragonal axes at A, trigonal axes at O, digonal axes at D. Repetition of the plane (321) about these axes gives rise to the form of Fig. 110, whose poles are shown in Fig 109. This form is called a *pentagonal icositetrahedron*, since it consists of twenty-four pentagons (not regular). Now if the form {231} be constructed (Fig. 111) it will be found that the two forms, though precisely similar, are not identical. They will bear the same relation to one another which a right-hand bears to a left-hand glove; the one is the inverse or reflection of the other. Two supplementary forms which are similar but not identical are said to be "enantiomorphous"; all forms

which have neither a centre nor a plane of symmetry are enantiomorphous to another form. The forms belonging to the two preceding classes are not enantiomorphous figures, because they possess planes of symmetry.

In the cuprite class it will be found that all the forms are the same

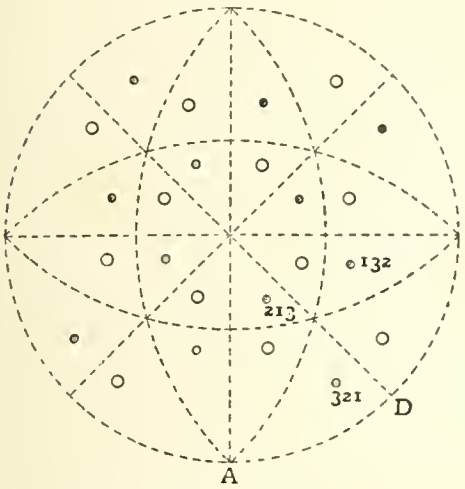


Fig. 109.—Cubic, Holoaxial (Tesseral Holoaxial).

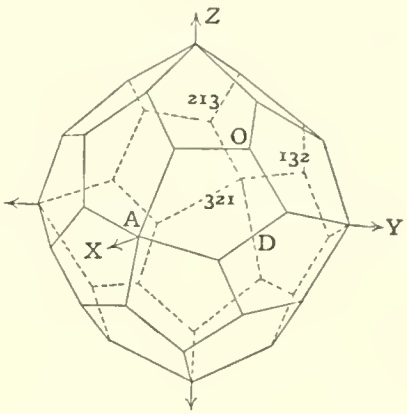


Fig. 110.—Pentagonal Icositetrahedron.

as those in the holosymmetric class, with the exception of $\{hkl\}$, which is no longer a six-faced octahedron, but the form of Fig. 110 or 111. For this reason minerals belonging to this class will not betray their true symmetry unless they exhibit faces of such a form. Cuprite, although very rich in faces, usually presents only combinations of cube, octahedron,

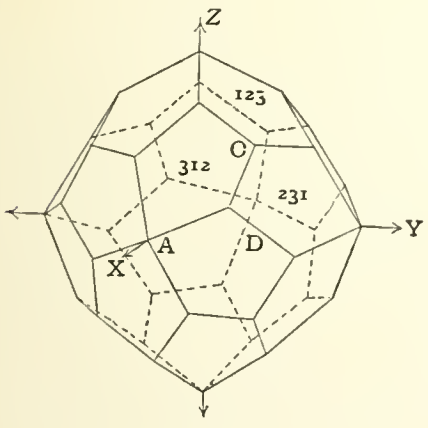


Fig. 111.—Enantiomorph of Fig. 110.

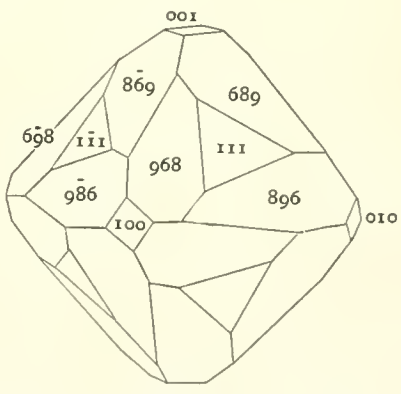
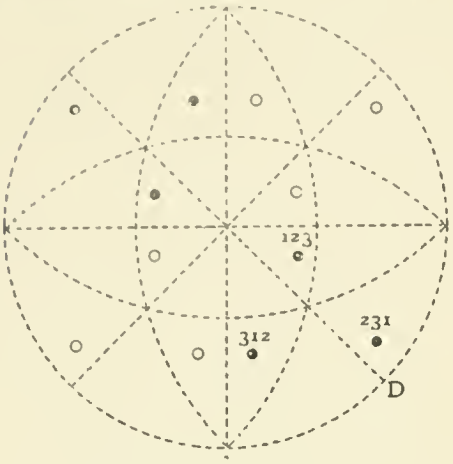


Fig. 112.—Cuprite from Cornwall.

dodecahedron, and icositetrahedron without faces of $\{hkl\}$. Fig. 112 represents a rare type of cuprite from Liskeard in Cornwall, a combination of cube $\{100\}$, octahedron $\{111\}$, and the form $\{896\}$.

29. **The Ullmannite Class.**—The crystals of this class possess four polar trigonal axes, and consequently also three digonal axes. All the forms are the same as one or other of those in the preceding classes

with the exception of {*hkl*}, which is shown in Fig. 114. The form {111} is a tetrahedron and {210} is a pyritohedron.



113.—Cubic, Trigonal Polar (Tesseral Polar).

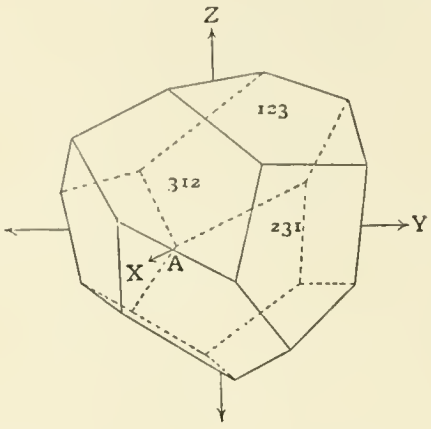


Fig. 114.

Crystals of ullmannite from Carinthia are tetrahedral, those from Sardinia are pyritohedral, clearly indicating that the mineral belongs neither to the pyrites class nor to the tetrahedrite class. Sodium chlorate also belongs to this class.

The Tetragonal System

Crystals referable to three rectangular axes, two of which are equal. The crystals of this system possess one axis of fourfold symmetry.

30. **Tetragonal System—Holosymmetric Class.**—The crystals of this class possess one ditetragonal axis and a centre of symmetry. Two similar planes of symmetry S, at right angles to each other, are accompanied by a second such pair Σ, and by the equatorial plane of symmetry R. The ditetragonal axis emerges at C, and di-digonal axes at A, D, and the corresponding points. The five planes of symmetry are projected as in Fig. 115, so that the principal axis occupies the centre C of the circle of projection. The various forms may be ascertained, as in the cubic system, by considering the possible positions of a pole on the sphere with regard to the triangle ADC formed by three circles of symmetry. The pole must fall either upon an angle, or upon a side, or within the triangle.

(1) *Tetragonal Prism* {110}; *prism of the first order.*—A pole situated at D, when repeated over the S planes of symmetry, gives rise to a form having four faces, which constitute a prism with a square base (Fig. 116).

The tetragonal prism {110} is not a closed figure and can only yield

one by combination with some other form; in Fig. 116 it is terminated by the faces (001) and (00$\bar{1}$), but the fact that these belong to a different form is here indicated by their smaller size.

(2) *Tetragonal Prism* {100}; *prism of the second order.*—When the pole is situated at A the form is another tetragonal prism precisely similar

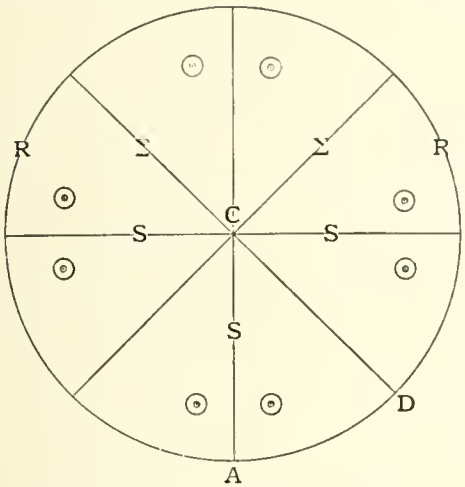


Fig. 115.—Tetragonal System. Holosymmetric.

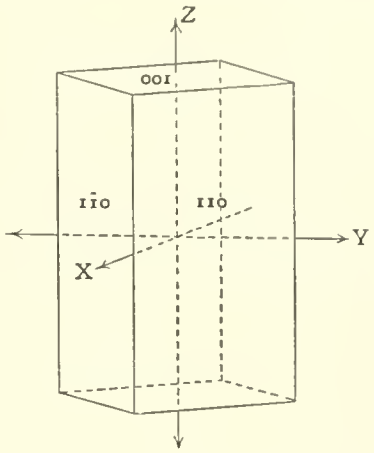


Fig. 116.—Tetragonal Prism: First order.

to the first. Geometrically speaking Fig. 117 is merely Fig. 116 turned through 45°, but in a tetragonal crystal there will always be differences in the surface of the faces, or in other physical characters which serve to distinguish the one form from the other. This is also an open form.

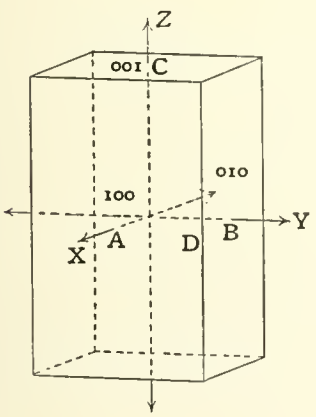


Fig. 117.—Tetragonal Prism: Second order.

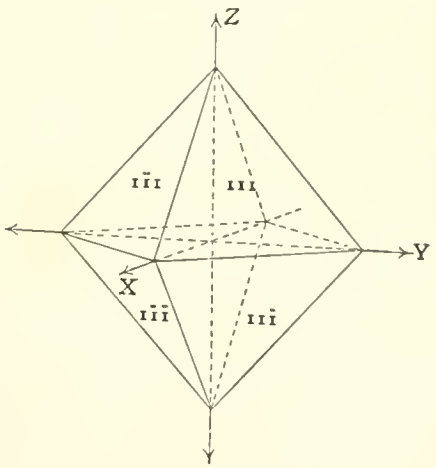


Fig. 118.—Tetragonal Bipyramid: First order.

Since in passing from the cubic to the tetragonal system four of the dodecahedral planes of symmetry have disappeared, the faces (001) and (00$\bar{1}$) do not now belong to this form.

(3) *Basal Pinakoid* {001}.—When the pole is situated at C the form consists merely of the pinakoid or pair of parallel faces (001) and (001) which constitute the summit and base of Figs. 116, 117. In this or any

of the following systems, a face which intersects the vertical axis, OZ, and is parallel to the two lateral axes, OX, OY, is called the "basal plane." Idocrase, from Wilui in Siberia, is found in square prisms terminated by the basal pinakoid.

(4) *Tetragonal Bipyramid {hhl}; pyramid of the first order.*—When the

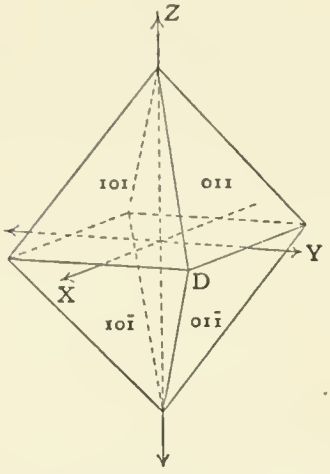


Fig. 119.—Tetragonal Bipyramid: Second order.

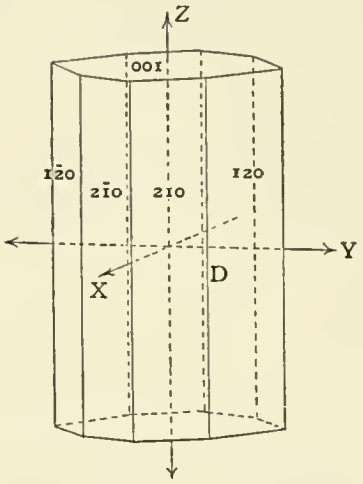


Fig. 120.—Ditetragonal Prism.

pole is situated upon the arc CD, the intercepts made by the corresponding face upon the two lateral axes are equal, and the first two indices in the symbol must also be equal; the form is therefore *{hhl}*, where *h* and *l* may have any values (Fig. 118). When the face belongs

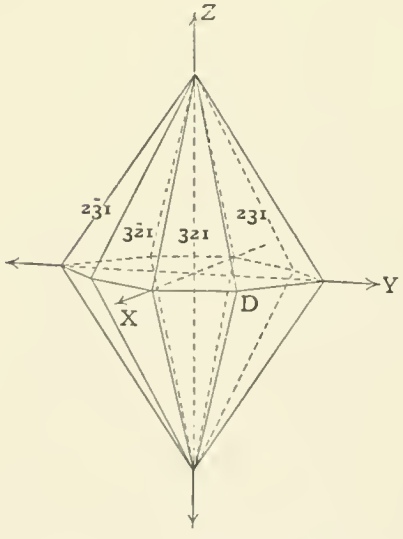


Fig. 121.—Ditetragonal Bipyramid.

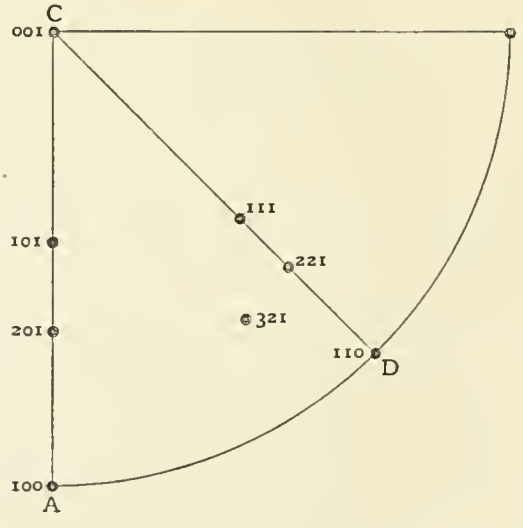


Fig. 122.

to the parametral form selected to determine the axial lengths its symbol is (111).

(5) *Tetragonal Bipyramid {h0l}; pyramid of the second order.*—When the pole is situated on the arc AC it again belongs to a four-faced bipyramid *{h0l}*, in which *h* and *l* may have any values (Fig. 119). When

the intercepts made by this form on the lateral and vertical axes are chosen to determine the axial lengths it is the parametral form {101}. This form, like the last, is a pyramid having a square base, but the two are not identical, since {101} has the two equal axes parallel to the sides of its base, while {111} has the same axes for the *diagonals* of its base; consequently the two pyramids, if they have the same height, cannot have equal bases, and conversely, if they have the same base, one must be longer or shorter than the other. Anatase is often found in simple bipyramids with a square base.

(6) *Ditetragonal Prism* {*hk*0}.—When the pole falls upon the arc AD it must be repeated over both the S and Σ planes of symmetry and becomes an eight-faced prism (Fig. 120). This, combined with the basal pinakoid, is found as a form of idocrase.

(7) *Ditetragonal Bipyramid* {*hkl*}.—When the pole falls within the triangle ADC it must be repeated over all the planes of symmetry and gives rise to the sixteen-faced bipyramid (Fig. 121), of which Fig. 115 is a projection. Such a form is only known in combination.

The positions of the poles of the preceding seven forms are shown in Fig. 122.

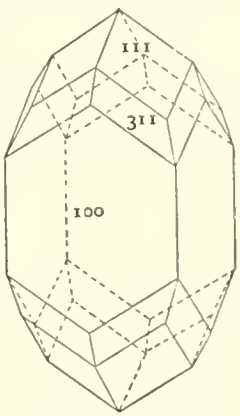


Fig. 123.—Zircon from Miask.

Fig. 123 is a crystal of zircon from Miask, in the Urals, a combination of the forms {111} {100} {311}.

It will be observed that in a crystal belonging to the tetragonal system the direction of the vertical axis is fixed, since it coincides with the principal axis of symmetry. On the other hand, it is a matter of choice whether a given square prism is called a prism of the first or the second order. The crystal of Fig. 118 might either be called a square pyramid of the first order {111}, or be turned through 45° and called a square pyramid of the second order {101}. Whichever position is adopted for one crystal is of course retained for all crystals of the same mineral.

31. **The Chalcopyrite Class.**—The crystals of this class possess two planes of symmetry at right angles to each other, intersecting in a ditetragonal axis of alternating symmetry, and there is no centre of symmetry. Repetition of the plane (321) about these elements of symmetry gives the *scalenohedron* of Fig. 125, whose poles are shown in Fig. 124.

The axis is not merely di-digonal, for each face can be derived from another face of the scalenohedron by a rotation of 90° about the vertical axis, combined with reflection over the equatorial plane, *e.g.* $(\bar{2}3\bar{1})$ from (321); rotation brings it to $(\bar{2}31)$, reflection to $(\bar{2}31)$. Such an axis is one of "alternating" symmetry.

The only other form of this class besides {*hkl*} which differs from that of the holosymmetric class is that whose pole lies upon a plane of symmetry (but not at D), viz. {*hhl*} or {111}.

This class corresponds closely to the tetrahedrite class in the cubic

system; thus the form (Fig. 126) is very similar in appearance to the tetrahedron, but is in reality a *bisphenoid* or double wedge, whose faces

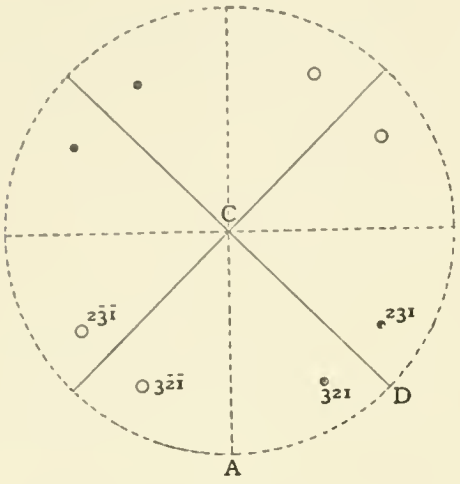


Fig. 124.—Ditetragonal alternating.

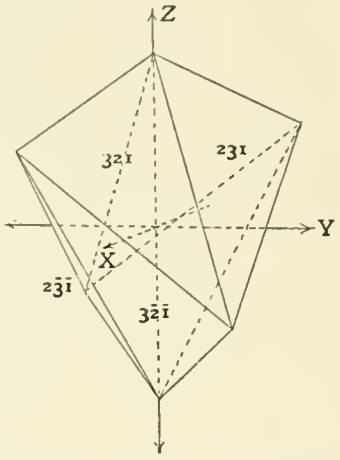


Fig. 125.—Tetragonal Scalenohedron.

are isosceles and not equilateral triangles, since the vertical axis Z is not equal in length to the lateral axes X and Y. Fig. 127 is a crystal of chalcopyrite from Pennsylvania, a combination of the

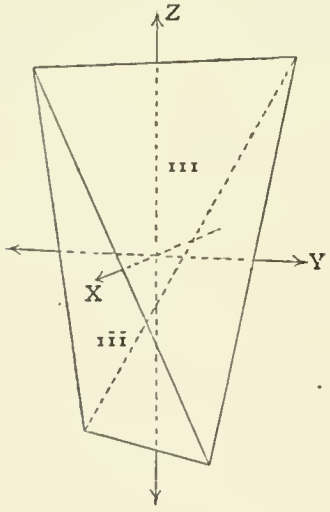


Fig. 126.—Bisphenoid.

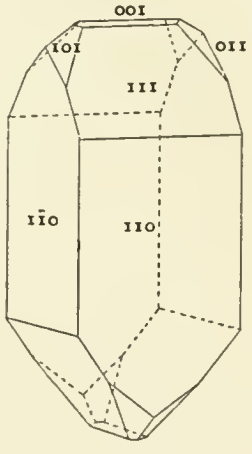


Fig. 127.—Chalcopyrite from Pennsylvania.

forms:—square prism {110}, bisphenoid {111}, bipyramid {101}, basal pinakoid {001}.

32. **The Scheelite Class.**—The crystals of this class possess a tetragonal axis Z perpendicular to an equatorial plane of symmetry; they are therefore also centrosymmetrical. The face (321) repeated about these elements of symmetry gives rise to the *tetragonal bipyramid* of the third order (Fig. 129), whose poles are shown in Fig. 128.

The only other form which differs from the corresponding form in the holosymmetric class is the prism $\{hk0\}$, which is no longer a ditetragonal but a *tetragonal prism* of the third order (Fig. 130).

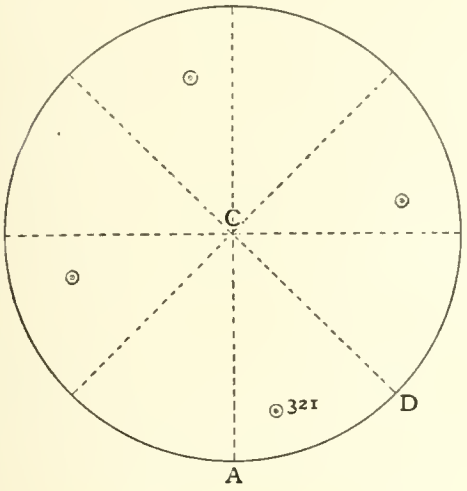


Fig. 128.—Tetragonal Equatorial.

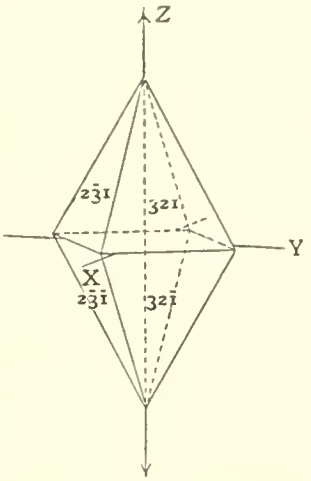


Fig. 129.—Tetragonal Bipyramid : Third order.

The crystallographic axes X and Y are not axes of symmetry in this class, neither do they in general emerge through the corners or edges of the forms. In this respect Figs. 129, 130 differ from Figs. 118, 116.

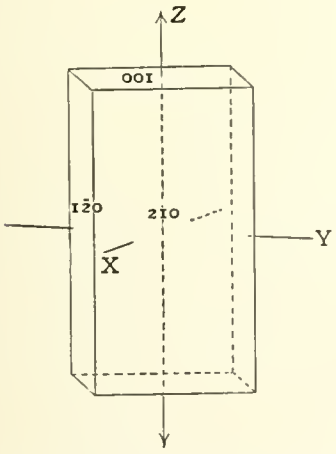


Fig. 130.—Tetragonal Prism : Third order.

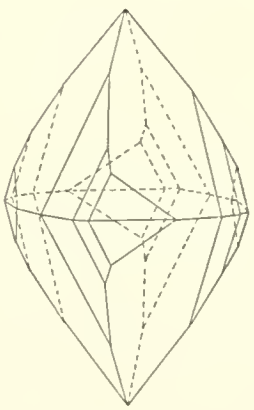


Fig. 131.—Scheelite.

Fig 131 is a crystal of scheelite from Zinnwald in Bohemia, a combination of four square bipyramids.

33. **The Wulfenite Class.**—The crystals of this class possess only a polar tetragonal axis Z. Repetition of the face (321) about this axis gives rise to the *tetragonal pyramid* of Fig. 133, whose poles are shown in Fig. 132. As in the last class, $\{hk0\}$ is here also the tetragonal prism

of Fig. 130. Further, since the tetragonal axis is polar, the form {001} is here not a pinakoid but a single basal plane.

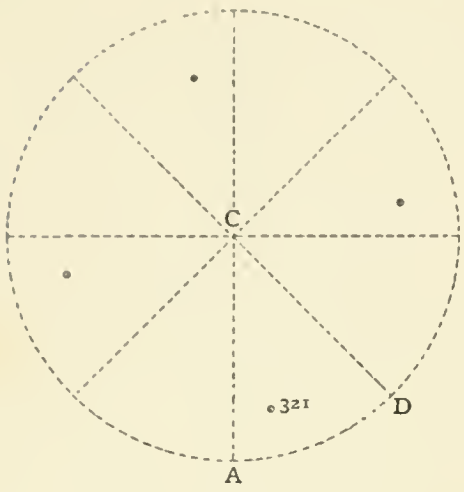


Fig. 132.—Tetragonal Polar.

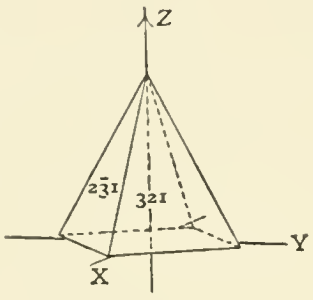


Fig. 133.—Tetragonal Pyramid.

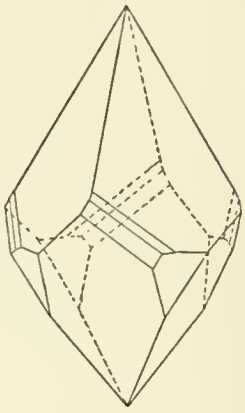


Fig. 134.—Wulfenite.

Fig. 134 represents a crystal of wulfenite from Saxony, a combination of five square pyramids.[1]

34. **The Axial Ratio.**—In the cubic system the three axes were equal, but in a tetragonal crystal the vertical axis c is either greater or less than the two lateral axes a. When the axial ratio $a : c$ is known, the

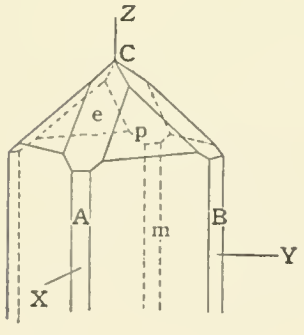


Fig. 135.

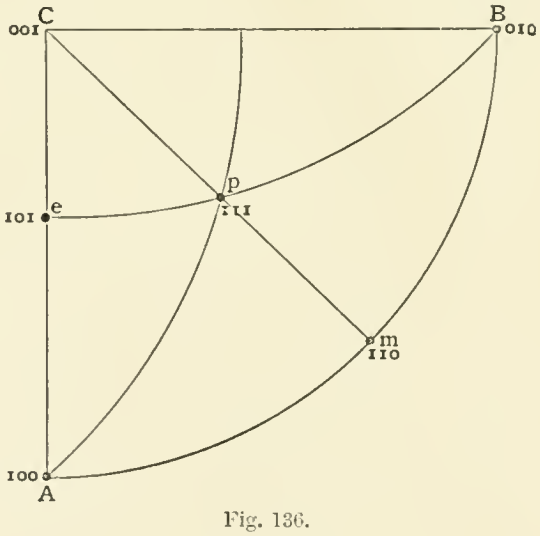


Fig. 136.

actual lengths of the intercepts made by any face are also known from its indices, and from these its inclination to the axes and to other faces may be calculated. The axial ratio is found from an angle which gives the position of any face cutting the vertical axis and at least one lateral axis by means of the equations on p. 32.

[1] For the three remaining Tetragonal Classes (Ditetragonal Polar, Tetragonal Holoaxial, and Tetragonal Alternating) see p. 282.

Thus in the crystal of cassiterite (Fig. 135), choose e for (101), then

$$\frac{a}{1}\cos \mathrm{A}e = \frac{c}{1}\cos \mathrm{C}e,$$

or

$$\frac{a}{c} = \frac{\cos \mathrm{C}e}{\cos \mathrm{A}e} = \tan \mathrm{A}e;\ \text{since AC} = 90^\circ.$$

Or again, let p be chosen as (111), then

$$\frac{a}{1}\cos \mathrm{A}p = \frac{c}{1}\cos \mathrm{C}p,$$

therefore

$$\frac{a}{c} = \frac{\cos \mathrm{C}p}{\cos \mathrm{A}p} = \frac{\sin mp}{\cos \mathrm{A}p}\ \text{since C}m = 90^\circ.$$

Now in the right-angled spherical triangle $pm\mathrm{A}$ (Fig. 136) (right angle at m), $\cos \mathrm{A}p = \cos pm \,.\, \cos \mathrm{A}m = \cos pm \,.\, \cos 45^\circ$, therefore

$$\frac{a}{c} = \frac{\tan mp}{\cos 45^\circ}.$$

Hence the measurement of one suitable angle, for example $\mathrm{A}e$ or mp, is enough to determine the axial ratio.

The Orthorhombic System

Crystals referable to three unequal rectangular axes, and possessing an axis of twofold symmetry which is either the intersection of two planes of symmetry or perpendicular to two axes of symmetry.

35. **Orthorhombic System—Holosymmetric Class.**—The crystals belonging to this class possess a di-digonal axis in which two planes of symmetry intersect, and a centre of symmetry. These elements involve also the equatorial plane of symmetry and two di-digonal axes lying in it as shown projected in Fig. 137.

The three crystal axes are, as in the cubic and tetragonal systems, the intersections of the planes of symmetry, but in this system each axis is only one of di-digonal symmetry, and there is no axis of higher symmetry which can be taken for a principal axis, like the vertical axis of the preceding system.

In describing the form of any orthorhombic crystal there is nothing to determine which of the three axes shall be chosen for the vertical, but after the vertical axis has been selected the crystal is by a general convention always so placed that of the two lateral axes the one directed towards the observer is the shorter.

The three axes are then distinguished as the vertical axis (c), the brachy-diagonal or short axis (a), and the macro-diagonal or long axis (b).

The various forms are then found as before :—

(1) *Macro-pinakoid* {100}.—When the pole is situated at A the form

consists of a pair of faces parallel both to the vertical axis and the macro-diagonal, and therefore called the macro-pinakoid.

(2) *Brachy-pinakoid* {010}.—When the pole is at B the form consists of the pair of parallel faces which are parallel both to the vertical axis and to the brachy-diagonal, and is called the brachy-pinakoid.

(3) *Basal Pinakoid* {001}.—When the pole is at C the form consists of a pair of faces parallel to the two lateral axes (*a* and *b*).

Fig. 138 represents a combination of these three forms, and resembles the combination (Fig. 117) in the tetragonal system, with the difference that the orthorhombic crystal, being a combination of three different forms, is represented by a figure having three pairs of unequal-sized faces,

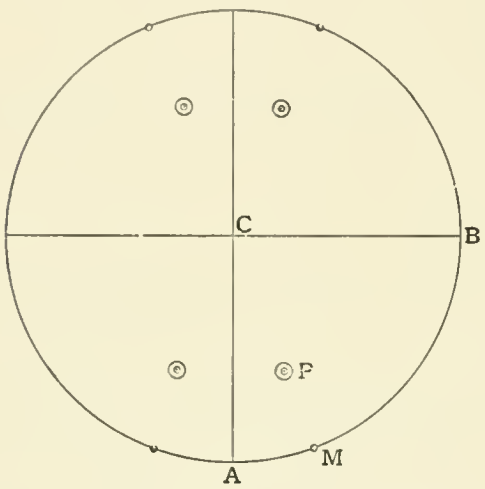


Fig. 137.—Orthorhombic System. Holosymmetric.

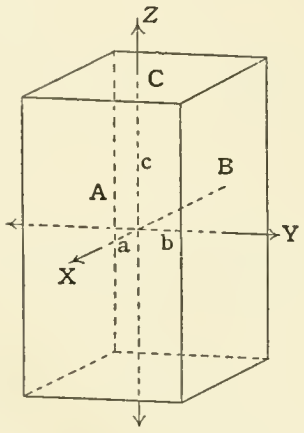


Fig. 138.—The three Pinakoids.

and in the real crystal these faces must have different physical properties (cf. the cleavage of anhydrite, p. 24).

When the pole lies upon one of the sides of the spherical triangle ABC formed by the three planes of symmetry, it belongs to a form consisting of four planes all parallel to one of the axes. In this, as in the preceding system, a form whose faces are parallel to the vertical axis is called a prism; a form whose faces are parallel to the macro-diagonal is called a macro-prism, and a form which is parallel to the brachy-diagonal is called a brachy-prism. These are of course open forms, and can only exist in combination in a complete crystal.

The next three forms are therefore:—

(4) *Prism* {*hk*0}.—When the pole lies upon the arc AB (as at M), the form is a prism having four faces parallel to the vertical axis. The particular prism which passes through the extremities of the lateral axes, or which is selected to determine the lengths of those axes, has the symbol {110}, and is a prism with rhombic base whose shorter diagonal is directed towards the observer; in other words, the primitive prism {110} is so placed that its obtuse angle is in front, and in the projection its poles lie nearer A than B (as at M, Fig. 137). The prism is represented in Fig. 139, combined with the basal pinakoid.

(5) *Brachy-prism* {0*kl*}.—When the pole falls upon the side CB (as at

L in Fig. 152), the form is an open prism similar in appearance to the last, but parallel to the brachy-diagonal. The particular brachy-prism whose faces pass through the extremities of the axes b, c, has the symbol {011}. A brachy-prism closed by the macro-pinakoid is represented in Fig. 140.

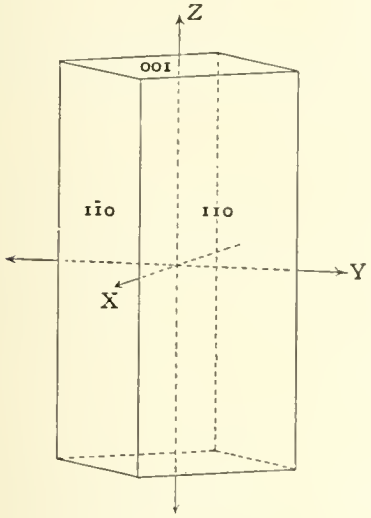


Fig. 139.—Rhombic Prism.

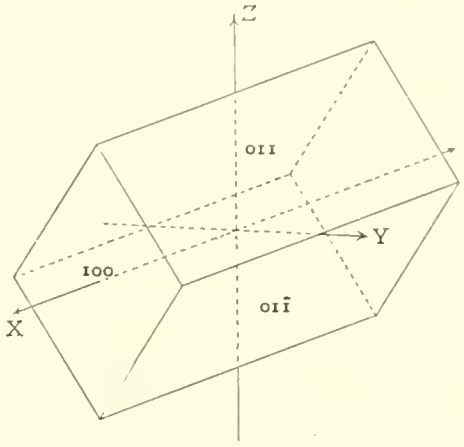


Fig. 140.—Brachy-prism.

(6) *Macro-prism* {$h0l$}.—When the pole is situated on AC (as at D in Fig. 152), the form consists of four faces parallel to the macro-diagonal; and the particular macro-prism whose faces pass through the extremities of the axes a, c, has the symbol {101}. Fig. 141 represents a macro-prism combined with the brachy-pinakoid.

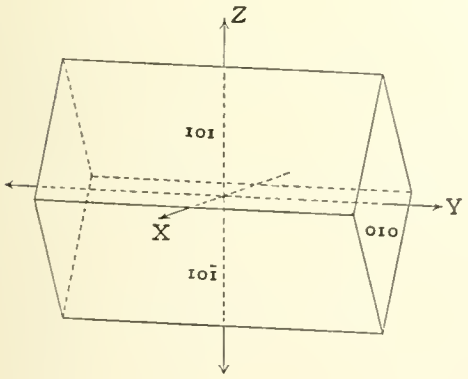


Fig. 141.—Macro-prism.

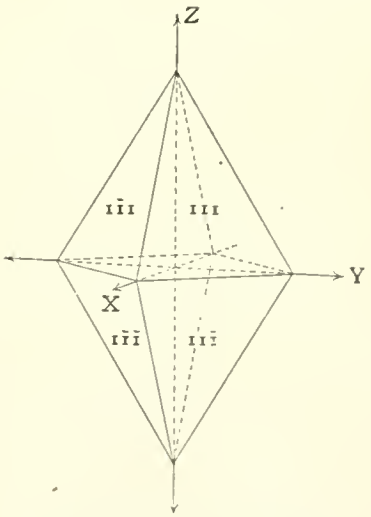


Fig. 142.—Rhombic Bipyramid.

(7) *Bipyramid* {hkl}.—Finally, when the pole falls inside the triangle ABC (as at P) the form consists of eight faces which constitute a bipyramid (Fig. 142) with rhombic base, shown in projection in Fig. 137. The parametral bipyramid {111} whose faces pass through the extremities of the three axes, or which is chosen to determine the length of the axes, must have its more obtuse angles in front and behind, and its more acute angles at the sides, when it is placed in the normal position.

Crystals bounded by the pinakoids alone (Fig. 138) are found in anhydrite; prisms terminated by the basal or other pinakoids alone are found in barytes.

Simple rhombic bipyramids are found among the crystals of anglesite. For holosymmetric combinations, see Figs. 583, 659, 662.

36. **The Sulphur Class.**—The crystals of this class are holoaxial and therefore possess three digonal axes coinciding with the crystal axes;

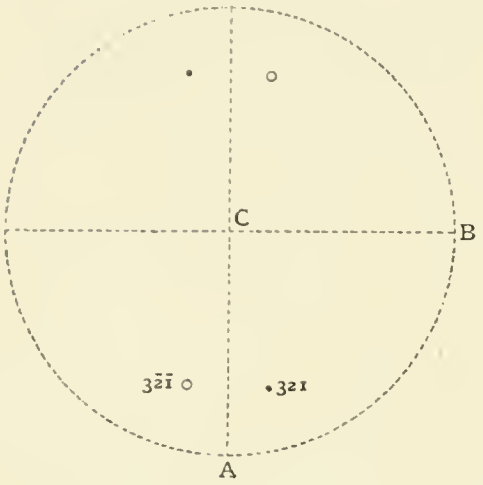


Fig. 143.—Holoaxial.

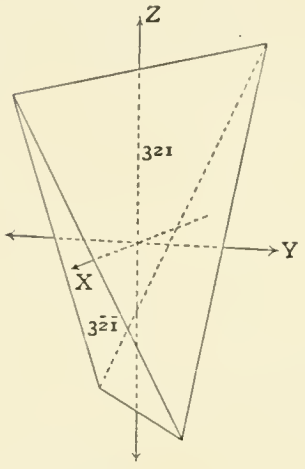


Fig. 144.—Bisphenoid.

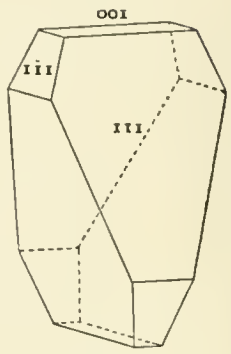


Fig. 145.—Sulphur.

they bear the same relation to those of the holosymmetric class that the tetrahedron bears to the octahedron. The face (321) (or any other pyramid face) repeated about these axes gives rise to the *bisphenoid* of Fig. 144, whose poles are shown in Fig. 143. All other forms are the same as in the holosymmetric class.

Sulphur from Sicily (Fig. 145) occasionally occurs in crystals presenting this symmetry; the figure represents a combination of $\{111\}$, $\{\bar{1}11\}$, $\{001\}$.

37. **The Hemimorphite Class.**—The crystals of this class possess one

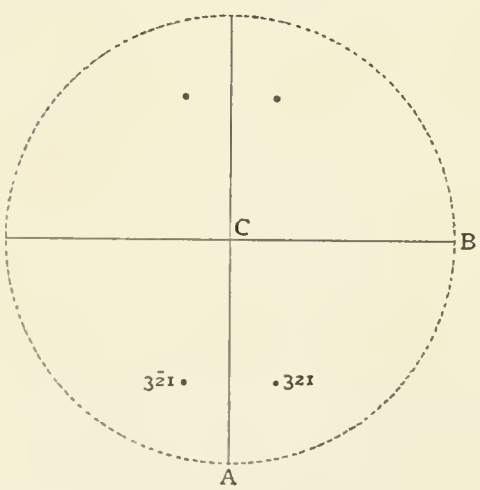


Fig. 146.—Polar.

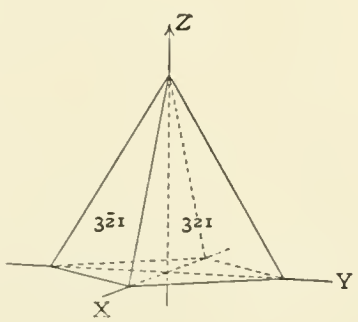


Fig. 147.—Rhombic Pyramid.

polar di-digonal axis Z, in which two planes of symmetry intersect. The

face (321) repeated about this axis, and about the two planes of symmetry which intersect in it, gives rise to the *rhombic pyramid* of Fig. 147, whose poles are shown in Fig. 146.

The other forms in this class which differ from the holosymmetric forms are the *brachy-dome* {0*kl*} (Fig. 148), the *macro-dome* {*h*0*l*} (Fig. 149),

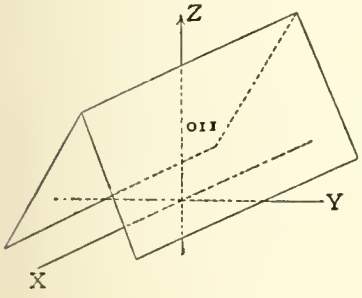


Fig. 148.—Brachy-dome.

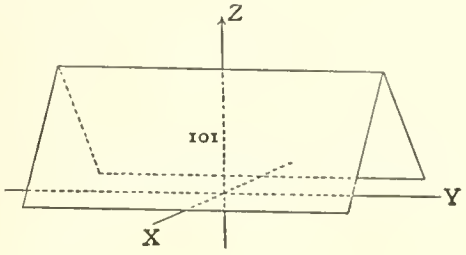


Fig. 149.—Macro-dome.

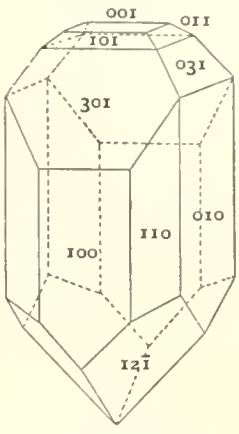


Fig. 150.—Hemimorphite.

and the *basal plane* {001}, which is no longer a pinakoid but a single face.

Hemimorphite from Aachen (Fig. 150) is a combination of the macro-pinakoid {100}, brachy-pinakoid {010}, macro-domes {101} {301}, brachy-domes {011} {031}, prism {110}, pyramid {12$\bar{1}$}, and basal plane {001}.

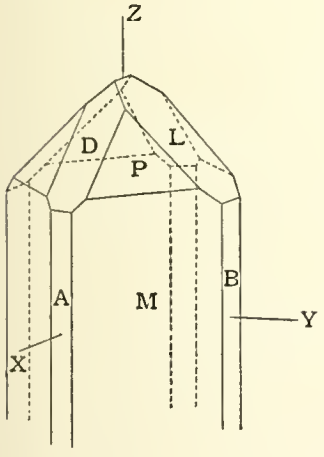


Fig. 151.

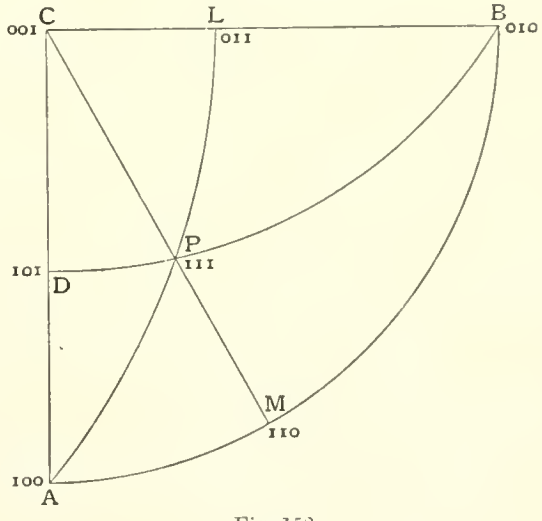


Fig. 152.

Crystals possessing a principal axis which is polar are sometimes called "hemimorphic," and the name of the mineral is derived from this peculiarity.

38. **The Axial Ratios.**—In the combination of Fig. 151 (which is to be compared with the projections Figs. 137 and 152), take M as (110),

P as (111), D as (101), L as (011). Then from the equations on p. 32, since AB = 90° —

$$\frac{a}{1}\cos \mathrm{AM} = \frac{b}{1}\cos \mathrm{BM} \therefore \frac{a}{b} = \frac{\cos \mathrm{BM}}{\cos \mathrm{AM}} = \tan \mathrm{AM}.$$

Similarly

$$\frac{b}{c} = \tan \mathrm{BL}, \text{ and } \frac{c}{a} = \tan \mathrm{CD}.$$

Hence the axial ratios may be determined by the measurement of two prism angles. If the faces which yield accurate measurements upon the crystal happen not to be those of a prism, but of the pyramid P, the formula becomes $a \cos \mathrm{AP} = b \cos \mathrm{BP} = c \cos \mathrm{CP}$; since the axes X, Y, Z coincide with the normals of A, B, C, and the points X, Y, Z on the projection coincide with the poles A, B, C.

The Hexagonal System

Crystals referable to three equal oblique axes and possessing one axis of threefold or of sixfold symmetry.

39. **The Hexagonal System; the two sorts of crystal axes.**— In the preceding systems the crystal axes have been three lines at right

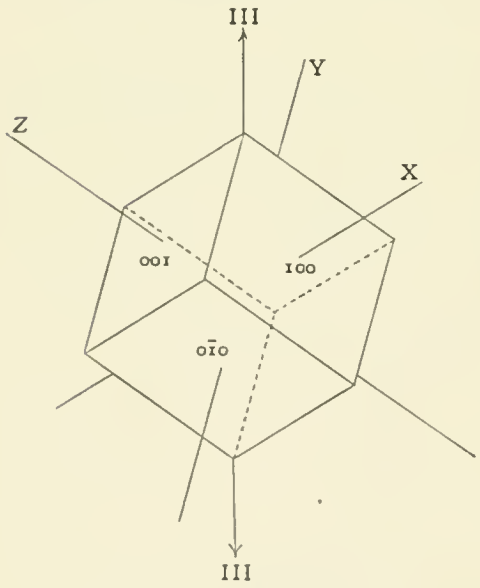


Fig. 153.—Crystal Axes of Cube.

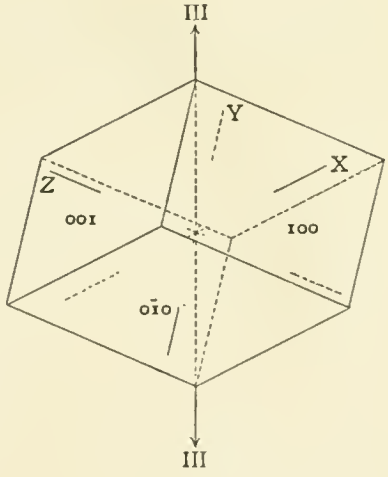


Fig. 154.—Crystal Axes of Rhombohedron.

angles to each other. We now come to a system in which three equal axes, not at right angles, are symmetrically disposed about a principal axis of trigonal or hexagonal symmetry.

The arrangement of the axes in such crystals is best understood by comparing them with those of a cube so placed that one of its diagonals (an axis of ditrigonal symmetry) is vertical, as in Fig. 153.

The figure most nearly resembling this among the forms of the hexagonal system is the rhombohedron (Fig. 154). The crystal axes being

chosen parallel to its edges, the symbols of its faces, like those of the cube, are (100) (010) (001); but, of course, the angles of the rhombohedron are not right angles.

The planes of symmetry passing through the three edges which meet in the apex of the crystal are shown in the projection (Fig. 155); it will be noticed that the axes X, Y, Z do not here (as in the cubic system) coincide with the normals to (100) (010) (001).

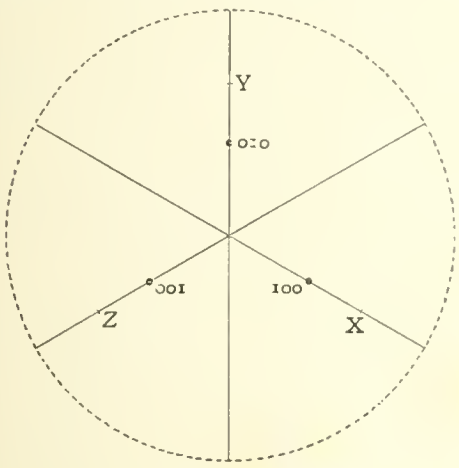


Fig. 155.—Symmetry Planes of Rhombohedron.

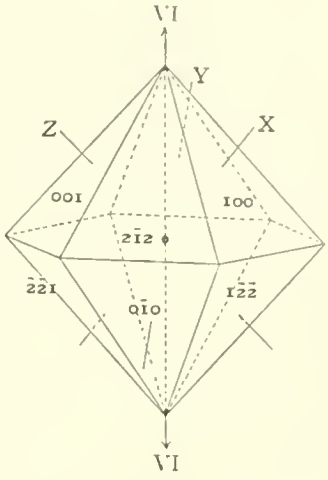


Fig. 156.—Combination of Direct and Inverse Rhombohedron.

The rhombohedron with three planes of symmetry is a form characteristic of some classes belonging to the hexagonal system; but the holosymmetric class possesses six planes of symmetry intersecting in a dihexagonal axis (Fig. 158). Now it was pointed out above that two different forms

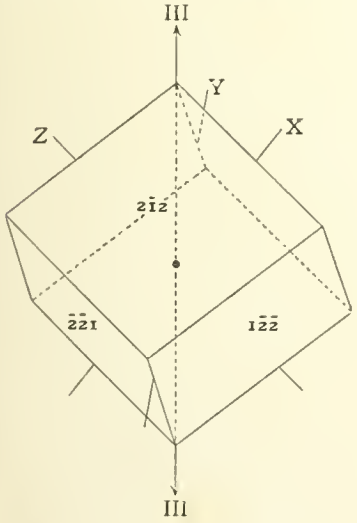


Fig. 157.—Inverse Rhombohedron.

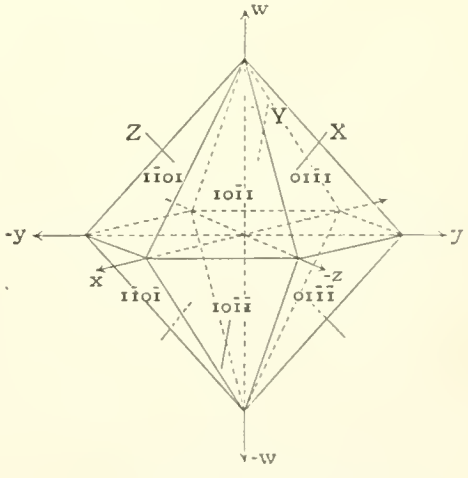


Fig. 158.—Hexagonal Bipyramid.

belonging to one class and having simple rational indices may, by their combination with each other, make up a form belonging to another class in the same system. Thus the two tetrahedra, $\{111\}$ and $\{\bar{1}\bar{1}1\}$, of Figs. 75, 77 make up the octahedron $\{111\}$ of Fig. 76 (Article 21). Similarly

the rhombohedron of Fig. 157 possesses simple rational indices; the front face intercepts the axes XYZ at distances $\frac{1}{2}$, 1, $\frac{1}{2}$ from the centre, and therefore has the symbol $(2\bar{1}2)$; and the combination of this rhombohedron with that of Fig. 155 resembles the hexagonal bipyramid of Fig. 156.

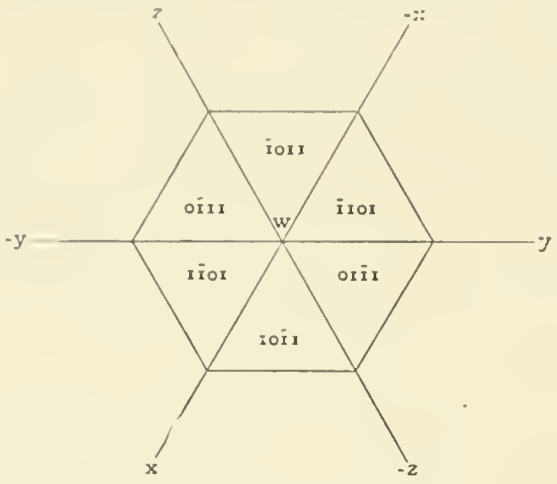


Fig. 159.—Hexagonal Bipyramid.

Two "rhombohedral" forms, such as $\{100\}$ and $\{2\bar{1}2\}$ which together make up a "hexagonal" form, are called a "direct" and an "inverse" form. Their indices hkl and efg are connected by the following relations:—

$$e = 2(h + k + l) - 3h$$
$$f = 2(h + k + l) - 3k$$
$$g = 2(h + k + l) - 3l$$

Thus if hkl be 010—

$$e = 2(0 + 1 + 0) - 0 = 2.$$
$$f = 2(0 + 1 + 0) - 3 = \bar{1}$$
$$g = 2(0 + 1 + 0) - 0 = 2$$

so that $(2\bar{1}2)$ is inverse to (010).

It seldom happens that the indices of the inverse form are composed of the same numbers as those of the direct; *e.g.* the face inverse to (321) is (369) or (123). When the direct and the inverse faces belong to the same form the crystal is, therefore, referred to four axes in order that all the faces of one form may be expressed by a single symbol.

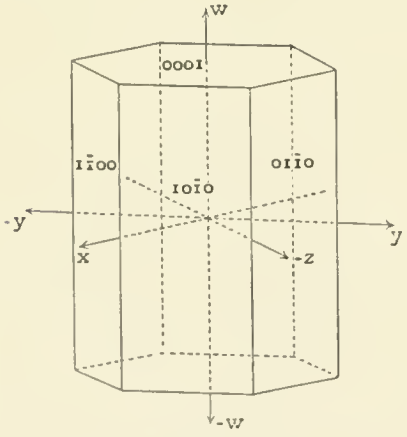


Fig. 160.—Prism of First Order.

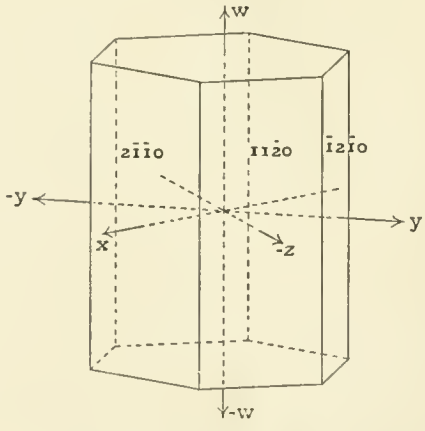


Fig. 161.—Prism of Second Order.

If referred to the three crystal axes XYZ, the hexagonal bipyramid must receive a double symbol—six of its faces are denoted by $\{100\}$, the other six by $\{2\bar{1}2\}$.

But the hexagonal bipyramid may be referred to the four "hexagonal axes" x, y, z, w, of Fig. 158, instead of the "rhombohedral axes" X, Y, Z. Fig. 159 represents the same form viewed from above. Each of

the horizontal axes, such as x, is perpendicular to the plane containing the corresponding rhombohedral axis X and the vertical axis w. The four axes x, y, z, w are axes of symmetry.

Referred to the hexagonal axes a face has not three but four indices $(hklm)$. The intercepts on the three axes x, y, z are not independent of each other; if two are positive the third is negative, and its value depends upon those of the first two. The relation is such that if two of the indices, h and k, are positive, then l is negative and equal to $h + k$. Thus with hexagonal axes the sum of the first three indices = 0.

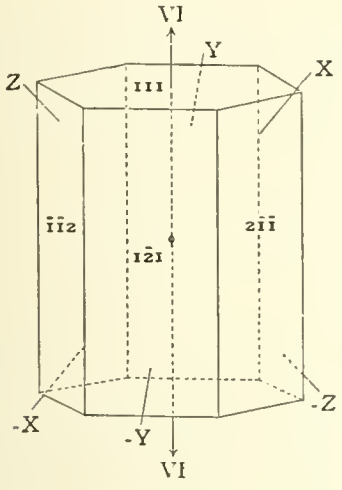


Fig. 162.—Prism of First Order.
(Rhombohedral Axes.)

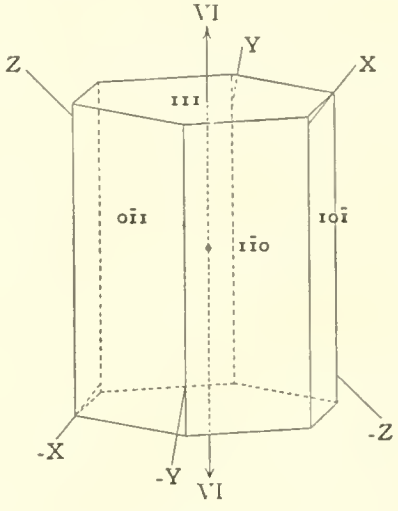


Fig. 163.—Prism of Second Order.
(Rhombohedral Axes.)

The indices of the two hexagonal prisms and the basal pinakoid are shown in Figs. 160-163. Figs. 160 and 162 represent the "hexagonal prism of the first order"; Figs. 161 and 163 represent the "hexagonal prism of the second order."

40. **Hexagonal System—Holosymmetric Class.** — The crystals of this class possess an axis of dihexagonal symmetry and a centre of symmetry; these involve an equatorial plane of symmetry perpendicular to the dihexagonal axis. The seven planes of symmetry are shown in the projection of Fig. 164. It will be seen from this figure and the form $\{12\bar{3}1\}$ of which it is a projection (Fig. 165) that the class also possesses six di-digonal axes which emerge at points such as a and M.

The possible forms in this class may be deduced by considering as before the possible positions of a pole upon the projection of Fig. 164; it must lie on a side or an angle of the triangle awM or within it, so that, as in the tetragonal system, there are seven varieties of forms:—

(1) *Basal Pinakoid* $\{0001\}$.—When the pole is at w the form consists of a pair of parallel faces; they are represented closing the ends of the prisms in Figs. 160, 161.

(2) *Hexagonal Prism of the First Order* $\{10\bar{1}0\}$.—When the pole is at M, the form is a hexagonal prism (Figs. 160, 162).

(3) *Hexagonal Prism of the Second Order* $\{11\bar{2}0\}$.—When the pole is at a, the form is a similar hexagonal prism (Figs. 161, 163).

(4) *Hexagonal Bipyramid of the First Order* $\{10\bar{1}1\}$.—When the pole falls upon wM, one side of the triangle waM, the form is a hexagonal

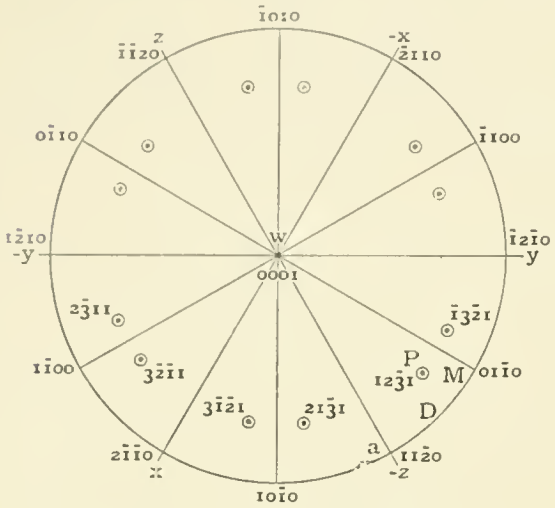


Fig. 164.—Dihexagonal Equatorial.

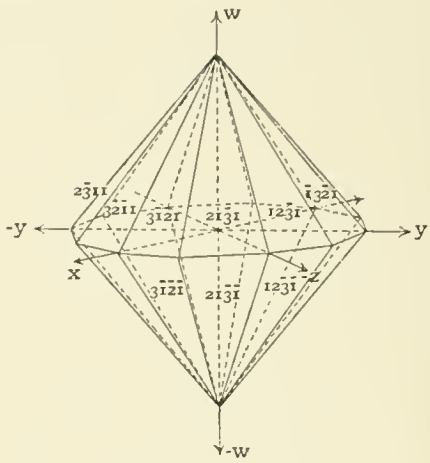


Fig. 165.—Dihexagonal Bipyramid.

bipyramid (Fig. 166), whose horizontal edges are the same as those of Fig. 160.

(5) *Hexagonal Bipyramid of the Second Order* $\{11\bar{2}1\}$.—When the pole falls upon wa, the form is a hexagonal bipyramid (Fig. 167), whose horizontal edges coincide with those of Fig. 161.

(6) *Dihexagonal Prism* $\{hkl0\}$.—When the pole falls upon aM (as at D), the form is the dihexagonal prism of Fig. 168.

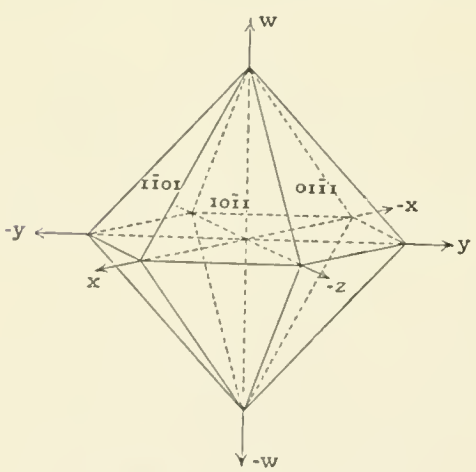


Fig. 166.—Bipyramid of First Order.

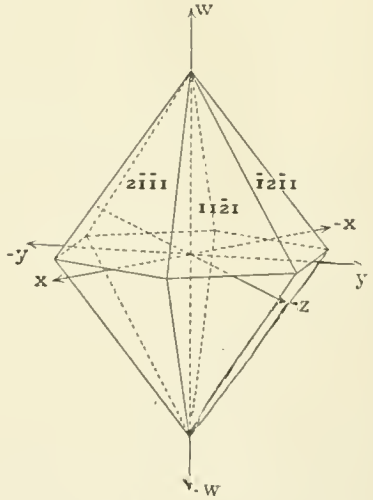


Fig. 167.—Bipyramid of Second Order.

(7) *Dihexagonal Bipyramid* $\{hklm\}$.—When the pole falls within the triangle, as at P, the form consists of twenty-four faces, and constitutes the dihexagonal bipyramid of Fig. 165, whose horizontal edges coincide with those of Fig. 168.

Of the above forms, simple hexagonal prisms combined with the basal pinakoid are common in beryl; but the other forms are only found in combination with each other or with the prisms and basal pinakoid.

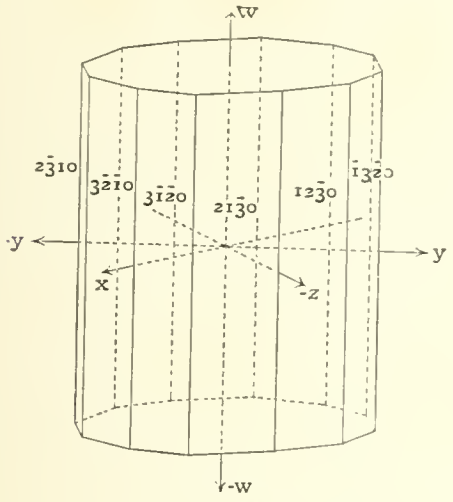


Fig. 168.—Dihexagonal Prism.

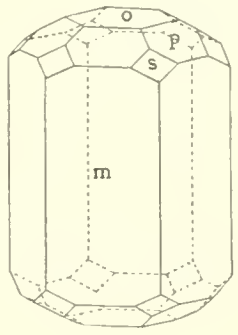


Fig. 169.—Beryl

Fig. 169 represents a crystal of beryl from Russia; $o = (0001)$, $p = (01\bar{1}1)$. $s = (11\bar{2}1)$, $m = (10\bar{1}0)$.

41. **The Calcite Class.**—The crystals of this class possess a dihexagonal axis of alternating symmetry (see section 21, p. 36). The figure which results from repetition of a plane about such an axis of symmetry is

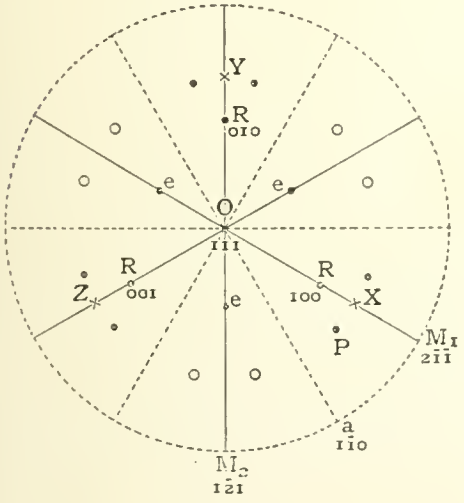


Fig. 170.—Dihexagonal Alternating.

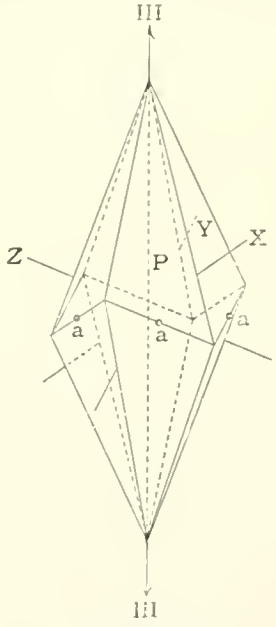


Fig. 171.—Scalenohedron.

the scalenohedron of Fig. 171. The three planes of symmetry, shown in the projection (Fig. 170), pass through those edges which meet at its apices, and there are also three digonal axes of symmetry emerging at the points a. The symmetry of this class may equally well be described as that of an axis of ditrigonal symmetry, combined with a centre of symmetry.

The varieties of forms possible in this class are found as before by considering the possible positions of a pole upon the sphere of projection.

(1) *Rhombohedron* $\{hkk\}$.—When the pole falls upon one of the planes of symmetry, like the poles of e (Fig. 170), the form consists of six faces, and is a rhombohedron (Fig. 172). When the pole falls between O and M_1 it is said to belong to a positive or direct rhombohedron, such as Fig. 155; when between O and M_2, to a negative or inverse rhombohedron, such as Fig. 172 or Fig. 157.

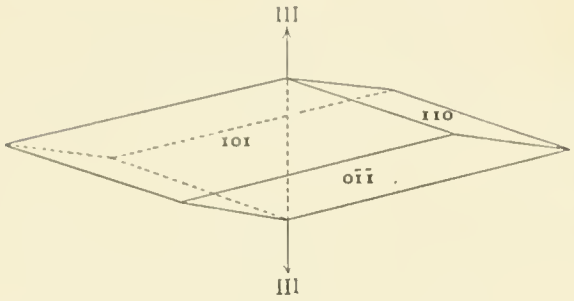


Fig. 172.—Rhombohedron.

When the pole is nearer to the centre O than the pole of (100), the rhombohedron is "obtuse," as in Fig. 172. When further from the centre than the pole of (100), the rhombohedron is "acute," as in Fig. 173.

In this class a rhombohedron has two equal indices, which may be either greater or less than the third; for a pole between R and M_1, for example, $m(100) + n(2\bar{1}\bar{1}) = (m + 2n, -n, -n)$: the particular rhombohedron, R, whose edges are parallel to the axes, is $\{100\}$, and the general symbol for any rhombohedron is $\{hkk\}$. It must be noted that the only faces whose indices are all positive are those whose poles lie on the projection within the triangle RRR corresponding to the positive octant ABC of the cubic projection. All direct rhombohedra which are more acute than R, and all inverse rhombohedra which are more acute than e, must therefore have one or two negative indices. In Figs. 177, 178 the obtuse rhombohedron e truncates the edges of R, and the acute rhombohedron s has its edges truncated by R. Every direct rhombohedron truncates the edges of a more acute inverse rhombohedron, and has its own edges truncated by the faces of a more obtuse inverse rhombohedron.

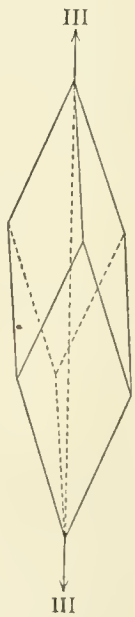


Fig. 173.—Rhombohedron.

(2) *Basal Pinakoid* $\{111\}$.—When the pole coincides with O the form is a pinakoid, as in the holosymmetric class (Figs. 162, 163).

(3) *Hexagonal Prism of the First Order* $\{2\bar{1}\bar{1}\}$.—When the pole lies at M the form is a hexagonal prism, as in the holosymmetric class (Fig. 162.)

(4) *Hexagonal Prism of the Second Order* $\{10\bar{1}\}$.—When the pole coincides with a it belongs to a hexagonal prism, as in the holosymmetric class (Fig. 163).

(5) *Dihexagonal Prism* $\{hkl\}$ $(h + k + l = 0)$.—When the pole lies on the circle of projection between M and a it belongs to a dihexagonal prism, as in the holosymmetric class (Fig. 168). The symbol of the zone $[a\mathrm{M}]$ found by cross-multiplying the symbols of a and M is [111].

Therefore if (hkl) is any face in this zone, $(h \times 1) + (k \times 1) + (l \times 1) = 0$ by article 8; hence the three indices of any prism face added together must equal 0.

(6) *Scalenohedron* $\{hkl\}$.—When the pole lies within the triangle M_1OM_2 there is one pole in each such triangle, and this, the most general form of the calcite class, consists of twelve faces, each in general a scalene triangle; the form (Fig. 171) is therefore called the scalenohedron, and its projection P is shown in Fig. 170. The scalenohedron resembles a bipyramid in having two apices on the principal axis, and differs from a bipyramid in having six lateral edges which are not horizontal, but form a zigzag. The edges coincide with the six lateral edges of some rhombohedron; the common scalenohedra of calcite have the same edges as

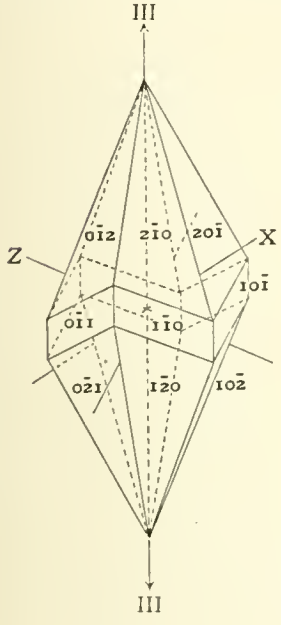


Fig. 174.

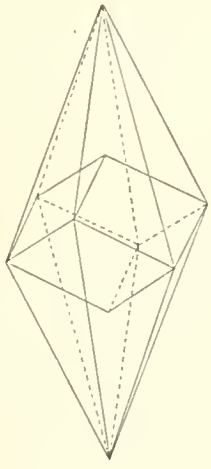


Fig. 175.

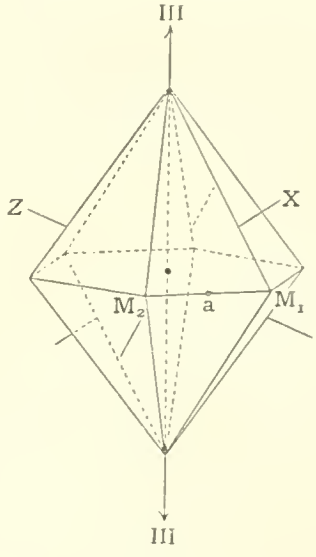


Fig. 176.

the rhombohedron $\{100\}$. Since each lateral edge of the rhombohedron is formed by the intersection of two similar faces, it is obvious that new forms may be derived from it either by truncating or bevelling these edges; the former process gives rise, as appears from Fig. 174, to the hexagonal prism $\{10\bar{1}\}$; the latter is illustrated by Fig. 175, which shows how the rhombohedron $\{100\}$ has the same zigzag edges with the scalenohedron $\{20\bar{1}\}$, which bevels its lateral edges. The poles of $\{20\bar{1}\}$ lie in the projection between the poles R, a, and the projection of the form is represented in Fig. 170.

(7) *Hexagonal Bipyramid* $\{hkl\}$ $\left(k = \frac{h+l}{2}\right)$.—In the particular case in which the pole falls midway between two planes of symmetry, *i.e.* on the zone $[Oa]$, the faces at the lower end of the crystal come immediately under those at the upper end; the edges of the scalenohedron become horizontal, and the form is converted into the hexagonal bipyramid of Fig. 176. Since a pole of this form lies between (111) and $(10\bar{1})$, and

since $m(111)+n(101)=(m+n,\ m,\ m-n)$—three numbers, of which the second is half the sum of the first and third—it follows that in the hexagonal bipyramid of the calcite class one index must always be the arithmetic mean of the other two.

Of the above forms, rhombohedra, both acute and obtuse, exist as

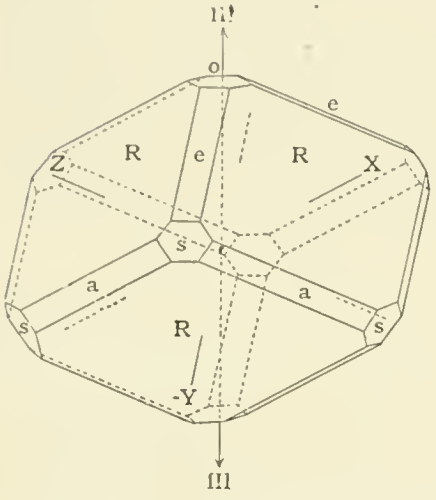


Fig. 177.

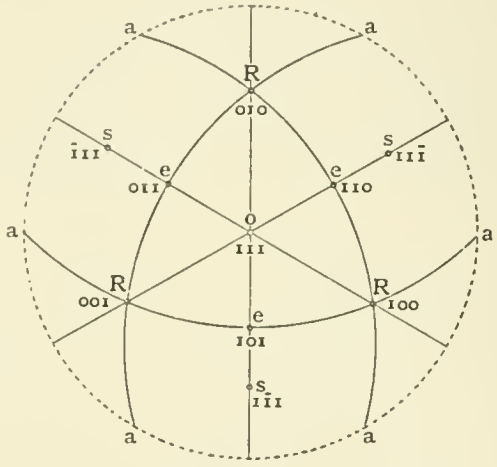


Fig. 178.

isolated forms on calcite; this mineral has also a perfect cleavage parallel to the faces of a rhombohedron, which is taken as the primitive form $\{100\}$.

The hexagonal prisms are both found as simple forms terminated by the basal pinakoid in calcite.

The scalenohedron $\{20\bar{1}\}$ is a very common simple form in the same mineral ("dog-tooth spar"); the acute hexagonal bipyramid $\{91\bar{7}\}$ has also been found on calcite from Rhisnes in Belgium and from Visby in Sweden. The dihexagonal prism is not known as a simple form, but is found in combination.

The close resemblance between crystals of this class and cubic crystals is well illustrated by such a combination as that of Figs. 177, 178, which is precisely analogous to that of the cube with octahedron and dodecahedron. If the whole figure were slightly elongated in the vertical direction, so that the form R became a cube, the combination would be that of the cubic system. The zones are the same as in the cubic combination, and therefore the indices are the same. Hence the crystal is a combination of the rhombohedron $R=\{100\}$, with the acute inverse rhombohedron $s=\{11\bar{1}\}$, the obtuse inverse rhombohedron $e=\{110\}$, the hexagonal prism $a=\{10\bar{1}\}$, and the basal pinakoid $o=\{111\}$.

42. **The Tourmaline Class.**—The crystals of this class possess a polar ditrigonal axis. Repetition about this axis and its planes of symmetry gives rise to the ditrigonal pyramid of Fig. 180, shown in projection in Fig. 179. The planes of symmetry pass through its edges.

The only other forms in this class which differ from those of the preceding classes are—

(1) The basal plane (111), which is no longer a pinakoid but a single plane, since the ditrigonal axis is polar.

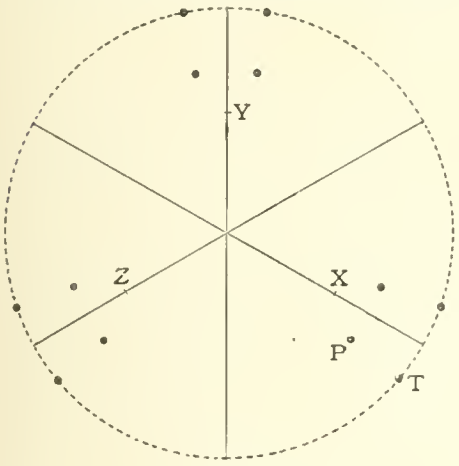


Fig. 179.—Ditrigonal Polar.

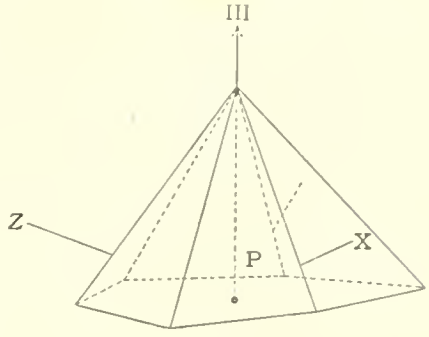


Fig. 180.—Ditrigonal Pyramid.

(2) The form $\{hkk\}$, which is not a rhombohedron but a trigonal pyramid (Fig. 181), having its faces perpendicular to the planes of symmetry.

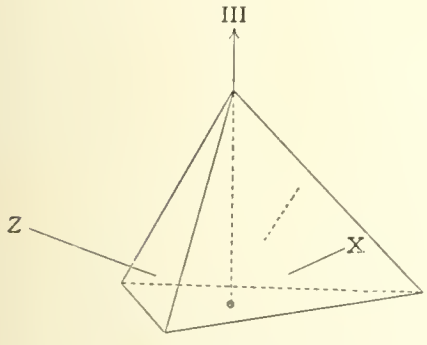


Fig. 181.—Trigonal Pyramid.

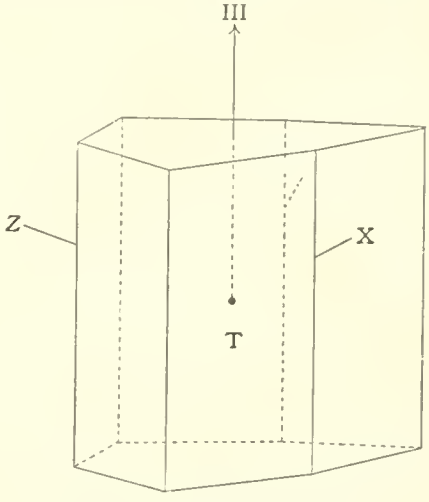


Fig. 182.—Ditrigonal Prism.

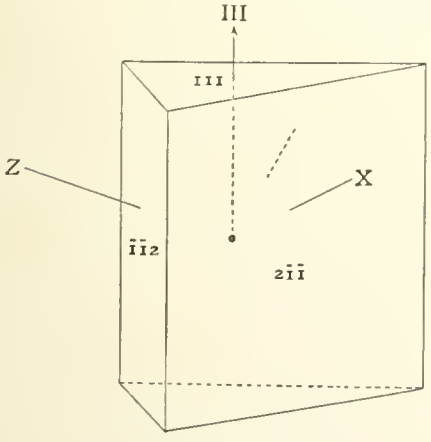


Fig. 183.—Trigonal Prism.

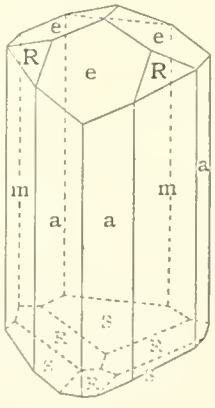


Fig. 184.—Tourmaline.

(3) The form $\{2\bar{1}\bar{1}\}$, which is no longer a hexagonal but a trigonal

prism (Fig 183), as may be seen by imagining one of the poles of Fig. 179 to migrate to a point M of Fig 164; the remaining poles will symmetrically migrate to only three such points.

(4) The form $\{hkl\}$, where $h+k+l=0$, a ditrigonal prism (Fig. 182).

(5) The form $\{hkl\}$, where $k=\frac{h+l}{2}$, a hexagonal pyramid (Fig. 85).

Fig. 184 represents a crystal of tourmaline from Elba—a combination of the pyramids $R=\{100\}$, $e=\{110\}$, $s=\{1\bar{1}\bar{1}\}$ trigonal prism $m=\{2\bar{1}\bar{1}\}$, hexagonal prism $a=\{101\}$.

43. **The Dioptase Class.**—The crystals of this class possess an alternating axis of hexagonal symmetry. Repetition of a plane about these elements of symmetry gives rise to the rhombohedron of Fig. 186 (shown in projection in Fig. 185), whose faces are not necessarily perpendicular to

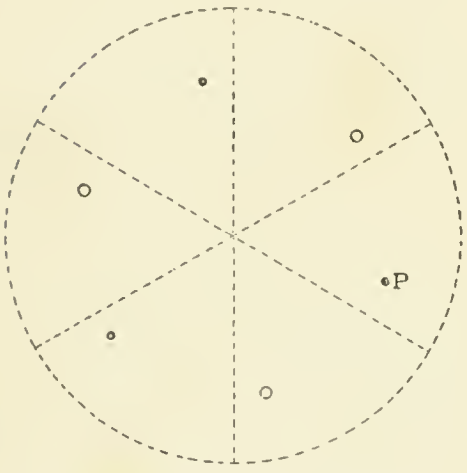


Fig. 185.—Hexagonal Alternating.

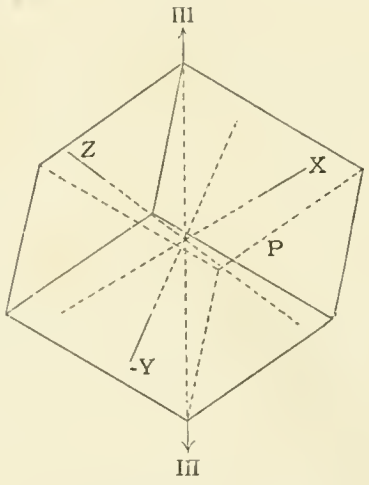


Fig. 186.—Rhombohedron.

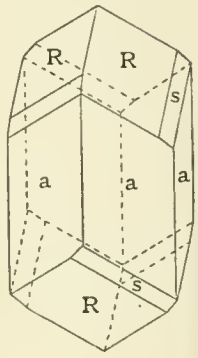


Fig. 187.—Dioptase.

vertical planes containing the crystal axes, as in the calcite class. The only other forms belonging to this class are hexagonal prisms and the basal pinakoid.

The symmetry of this class may equally well be described as due to a trigonal axis and a centre of symmetry.

Fig. 187 represents a crystal of dioptase from the Khirgis Steppes in Siberia, a combination of the forms:—$R=\{100\}$, $a=\{10\bar{1}\}$, $s=\{70\bar{1}\}$.

44. **The Quartz Class.**—The crystals of this class possess a trigonal axis of symmetry, and are holoaxial, or possess three polar digonal axes perpendicular to it. Repetition of a plane about these elements of symmetry gives rise to the "trigonal trapezohedron" of Fig. 189 (shown in projection in Fig. 188). The digonal axes emerge at the points A.

The other form in this class, which differs from forms previously considered in the hexagonal system, is the trigonal bipyramid of Fig. 190, whose poles, Q, lie in vertical zones through A, so that the faces intersect in horizontal edges, and not obliquely, as in Fig. 189. Its edges are identical with those of the base of the trigonal prism $\{1\bar{1}0\}$ (Fig. 191).

It must be observed that $\{2\bar{1}1\}$ is the trigonal prism in the tourmaline class, and $\{1\bar{1}0\}$ is the trigonal prism in the quartz class.

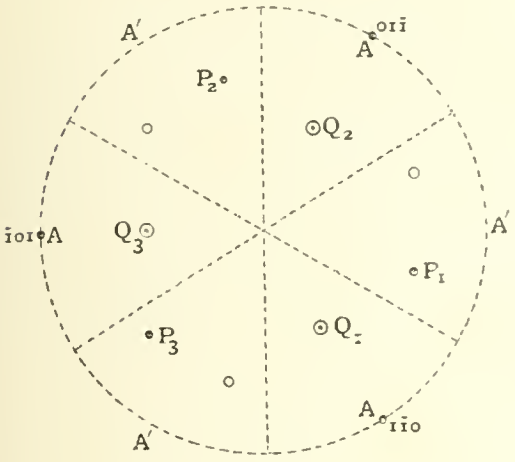


Fig. 188.—Trigonal Holoaxial.

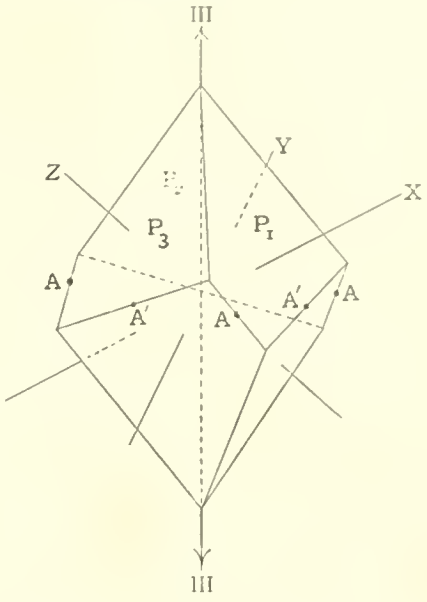


Fig. 189.—Trigonal Trapezohedron.

Fig. 192 represents a crystal of quartz, which is a combination of the rhombohedron $R = \{100\}$, with the inverse rhombohedron $z = \{2\bar{1}\bar{2}\}$, the hexagonal prism $m = \{2\bar{1}\bar{1}\}$, the trigonal bipyramid s, and the trapezohedron x.

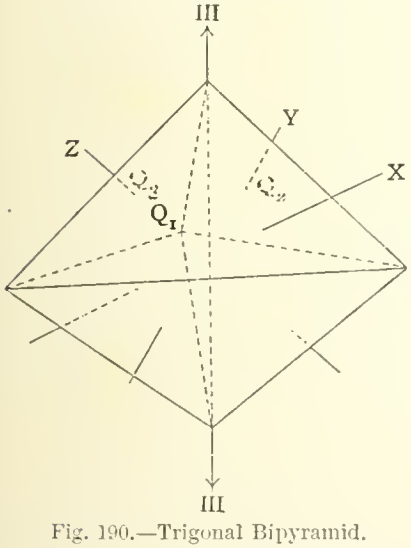


Fig. 190.—Trigonal Bipyramid.

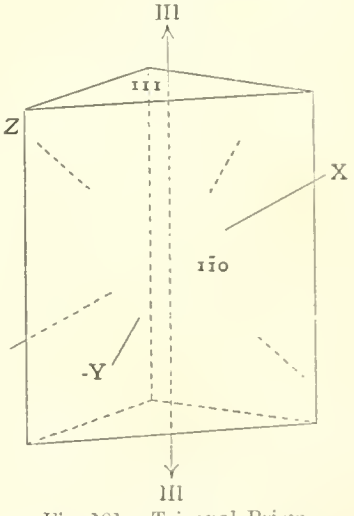


Fig. 191.—Trigonal Prism.

Crystals of the quartz class, like all holoaxial crystals, have neither a plane nor a centre of symmetry. Hence, as in the cuprite class, the crystal is "enantiomorphous"—its reflection in a mirror would have the appearance of Fig. 193, which bears the same relation to Fig. 192 that a left hand bears to a right hand. Both sorts of crystals are known.

Fig. 192 is called a right-handed crystal of quartz.

Fig. 193 is called a left-handed crystal of quartz.

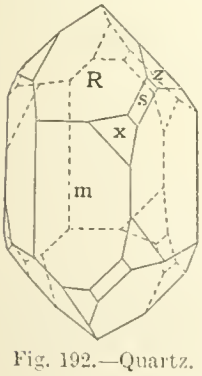


Fig. 192.—Quartz.

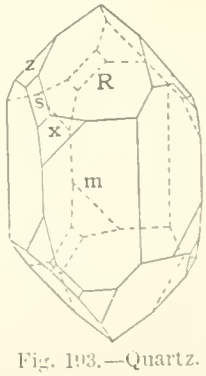


Fig. 193.—Quartz.

15. **The Greenockite Class.**—The crystals of this class possess a polar dihexagonal axis. Repetition of a plane about this axis and its planes of symmetry gives rise to the dihexagonal pyramid of Fig. 195; the planes of symmetry pass through its edges, as shown by the projection (Fig. 194). Forms corresponding to the bipyramids of the holosymmetric class are here all pyramids, and the form {0001} is a single basal plane and not a pinakoid. Fig. 196 represents a crystal of greenockite from Renfrewshire—a combination of the hexagonal pyramids $z\{20\bar{2}1\}$, $x\{10\bar{1}1\}$, $i\{10\bar{1}2\}$, $x'\{10\bar{1}\bar{1}\}$, with the basal plane $(000\bar{1})$, and the hexagonal prism $m = \{10\bar{1}0\}$.

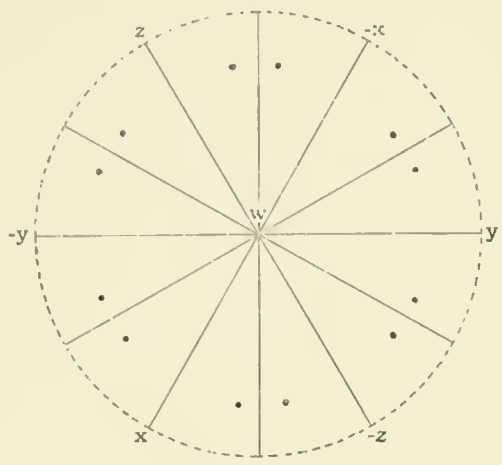


Fig. 194.—Dihexagonal Polar.

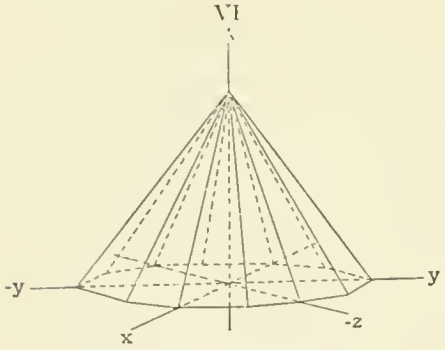


Fig. 195.—Dihexagonal Pyramid.

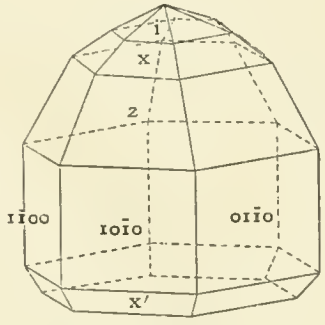


Fig. 196.—Greenockite.

46. **The Apatite Class.**—The crystals of this class possess a hexagonal

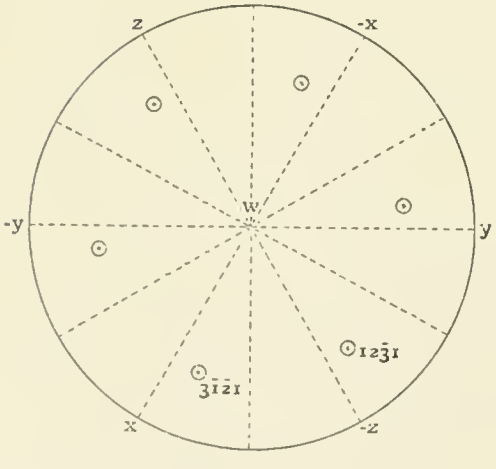


Fig. 197.—Hexagonal Equatorial.

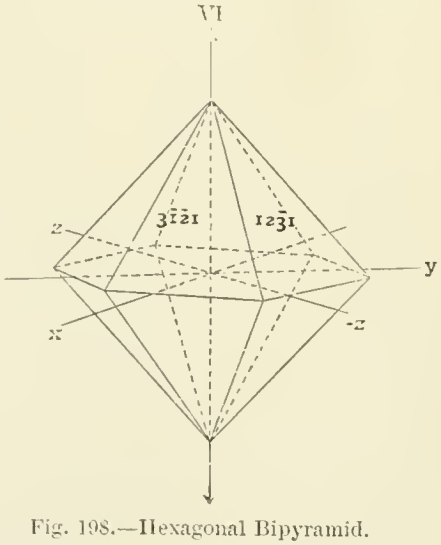


Fig. 198.—Hexagonal Bipyramid.

axis perpendicular to an equatorial plane of symmetry, and are therefore

also centro-symmetrical. Repetition of a plane about these elements of symmetry leads to a hexagonal bipyramid (Fig. 198), whose corners are not necessarily on the horizontal axes x y z, nor its edges perpendicular to them, as was the case in Figs. 166 and 167.

The other forms of this class are hexagonal prisms and the basal pinakoid. Fig. 199 represents a crystal of apatite from St. Gothard, a combination of the basal pinakoid $o = \{0001\}$ and hexagonal prism $m = \{10\bar{1}0\}$, with the hexagonal bipyramids $x = \{10\bar{1}1\}$, $\mu = \{21\bar{3}1\}$, $s = \{11\bar{2}1\}$.[1]

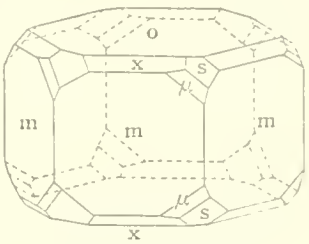


Fig. 199.—Apatite.

47. **The Axial Ratio or the Axial Angle.**—With the rhombohedral axes the parameters are equal [as determined by their intercepts with the basal plane (111)]; but the angle which the axes make with one another is

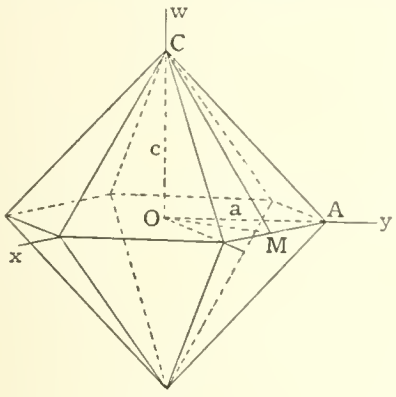


Fig. 200.

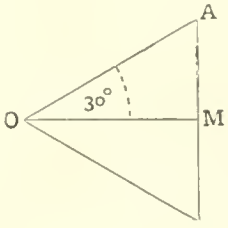


Fig. 201.

no longer a right angle, as was the case in the cubic system. It is the plane angle of the rhombohedron $\{100\}$ of Fig. 154, just as in the cubic system it is the plane angle of the cube.

In the system of hexagonal axes the length of the principal axis is denoted by c and that of the three lateral axes by a.

Then in Fig. 200, if C be the extremity of the vertical axis c,

$$\frac{c}{a} = \frac{\mathrm{OC}}{\mathrm{OA}}.$$

But $\mathrm{OA} = \frac{2}{\sqrt{3}}\mathrm{OM}$ from the plane triangle OAM (Fig. 201), since $\mathrm{MOA} = 30°$.

And also

$$\frac{\mathrm{OC}}{\mathrm{OM}} = \tan \mathrm{CMO}.$$

But CMO is the angle between the line CM in the plane $(01\bar{1}1)$ and the line OM in the basal plane (0001), so that

$$\mathrm{CMO} = \text{the angle } (01\bar{1}1 : 0001).$$

[1] For the five remaining hexagonal classes: Hexagonal holoaxial and polar, Ditrigonal equatorial, Trigonal equatorial and polar, see p. 281.

Hence

$$\frac{c}{a} = \frac{OC}{OA} = \frac{\sqrt{3}}{2}\,\frac{OC}{OM} = \frac{\sqrt{3}}{2}\tan(01\bar{1}1 : 0001).$$

The axis a is generally taken as unity.

The Monoclinic System

Crystals referable to Three Unequal Axes, one of which is perpendicular to the other two, and possessing either one Axis of Twofold Symmetry or one Symmetry Plane.

48. **The Monoclinic System. Holosymmetric Class.**—The crystals of this class possess a digonal axis which is perpendicular to a plane of symmetry. The manner in which crystals belonging to this system are drawn and projected is shown in Figs. 202 and 203.

The symmetry axis is perpendicular to the other two, which are

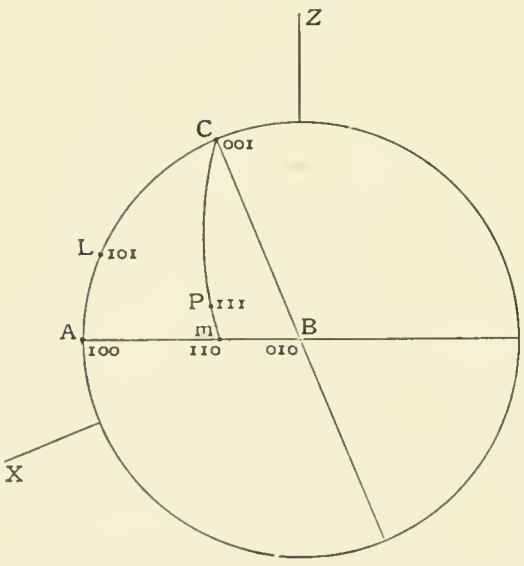


Fig. 202.—Method of Projecting the Monoclinic System.

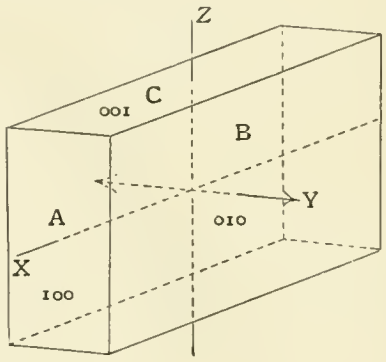


Fig. 203.—The Axial Pinakoids.

inclined to each other at some angle other than 90°, and lie in the plane of symmetry; the symmetry axis is chosen as Y (b axis); of the two remaining axes one, Z (c axis), is placed vertical, and the other, X (a axis), is placed so that the obtuse axial angle is in front (Fig. 203). In the projection the plane of symmetry XZ, which contains the a and c axes, is taken as the plane of the paper, so that Y coincides with the centre of projection and with the pole of B (010) and the obtuse axial angle is on the left; the crystal being supposed turned round as in Fig. 204. X and Z are the directions in which the a and c axes emerge from the sphere of projection; these do not coincide with the poles of any faces of the crystal, whereas in the three rectangular systems they coincide, as was seen above, with the poles 100 and 001.

The axis Y, which is perpendicular to the vertical axis, is called

the "ortho-diagonal." The axis X, which is inclined to the vertical axis, is called the "clino-diagonal."

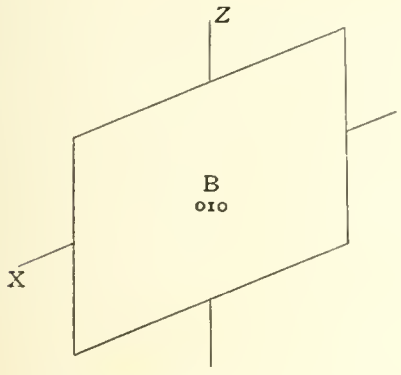


Fig. 204.

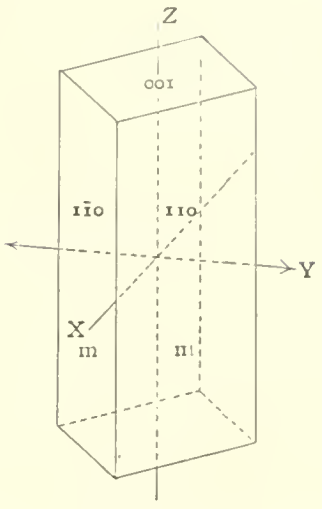


Fig. 205.—Prism.

In the monoclinic system there are no closed forms. The possible forms in the holosymmetric class are as follows:—

(1) *Ortho-pinakoid* {100}.—When the pole is at A the form consists of a pair of faces parallel to the ortho-diagonal and to the vertical axis.

(2) *Clino-pinakoid* {010}.—When the pole is at B the form consists of a pair of faces parallel to the clino-diagonal and to the vertical axis.

(3) *Basal Pinakoid* {001}.—When the pole is at C the form consists of a pair of faces parallel to the ortho- and clino-diagonals.

A combination of these three forms (whose intersections determine the directions of the axes) is shown in Fig. 203.

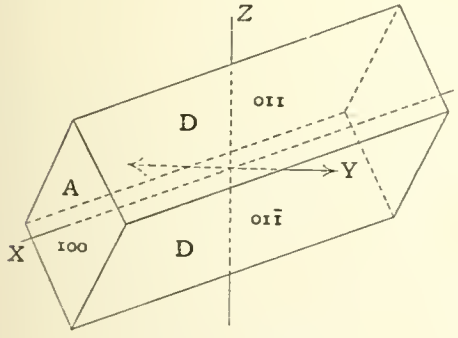


Fig. 206.—Clino-prism.

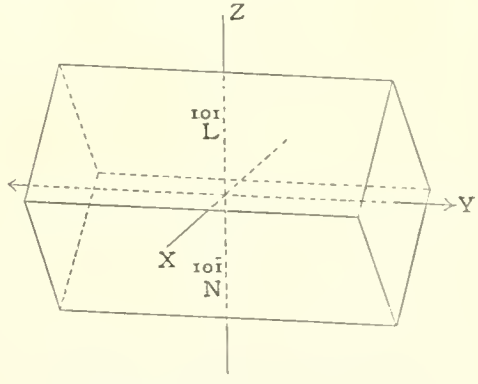


Fig. 207.—Ortho-prism consisting of two Hemi-prisms.

Forms whose faces replace the edges of Fig. 203, and whose poles therefore lie on the side of the triangle ABC, are parallel to one of the three axes. Those parallel to the vertical axis are called prisms: those parallel to the ortho-diagonal are called "ortho-prisms"; those parallel to the clino-diagonal are called "clino-prisms."

(4) *Prism* {*hk*0}.—When the pole lies between AB, as at *m*, the form consists of four faces parallel to the vertical axis (Fig. 205) and is a prism

with a rhombic base. The particular prism whose faces pass through the extremities of the lateral axes is {110}. This is shown in combination with the basal pinakoid in Fig. 205; the basal plane is oblique to the prism faces.

(5) *Clino-prism* {0*kl*}.—When the pole falls between B, C, as at D, the form consists of four faces parallel to the clino-diagonal. The clino-

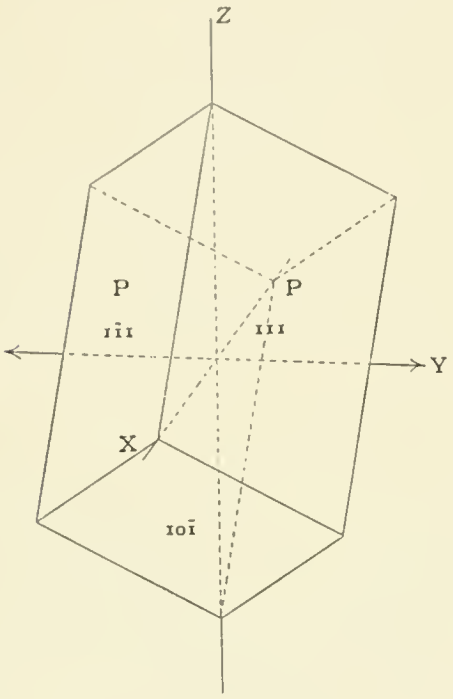


Fig. 208.—Hemi-pyramid.

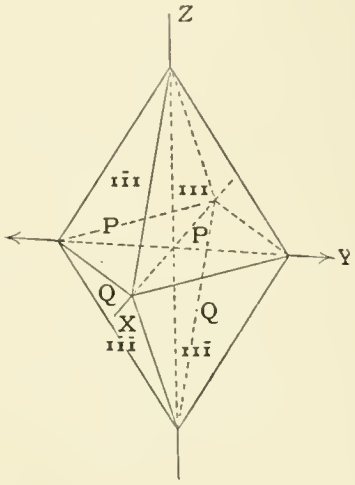


Fig. 209.—Monoclinic Bipyramid consisting of Two Hemi-pyramids.

prism whose faces pass through the extremities of the *b* and *c* axes has the symbol {011}. This is shown in combination with the ortho-pinakoid in Fig. 206; the clino-prism is oblique to the ortho-pinakoid.

(6) *Hemi-orthoprism* {*h*0*l*} or {*h*0$\bar{l}$}.—When the pole falls between A and C, as at L, the faces constitute a pinakoid or "hemi-prism" parallel to the orthodiagonal. The form whose faces pass through the extremities of the *a* and *c* axes has the symbol {101} (Fig. 207).

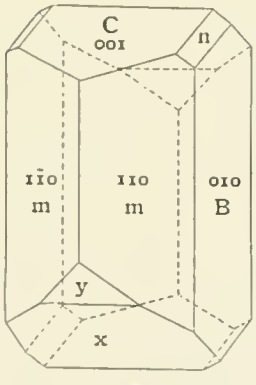


Fig. 210.—Orthoclase.

(7) *Hemi-pyramid* {*hkl*} or {*hk*$\bar{l}$}.—When the pole falls within the triangle ABC, as at P, the form is a prism or "hemi-pyramid" whose faces meet all three axes (Fig. 208). The form whose faces pass through the *extremities* of the three axes has the symbol {111}.

Monoclinic Pyramids and Ortho-prisms.—The hemi-prisms and hemi-pyramids which are situated in the obtuse angle of the axes XZ, whose symbols are therefore {*hkl*} and {*h*0*l*}, are often distinguished as negative forms, and those which are situated in the acute angle XZ, whose symbols are therefore {$\bar{h}$*kl*} and {$\bar{h}$0*l*}, are distinguished as positive forms. L and P are negative, N and Q are positive forms.

A negative and positive hemi-pyramid, such as $\{111\}$ and $\{\bar{1}11\}$, combined would make up a monoclinic bipyramid (Fig. 209), which really consists of the two forms P$\{111\}$ and Q$\{\bar{1}11\}$.

Similarly a negative and a positive hemi-prism combined make up an ortho-prism (Fig. 207).

Corresponding positive and negative forms often accompany each other in this class. Hence forms (6) and (7) are often spoken of as ortho-prisms and bipyramids respectively.

Fig. 210 represents a crystal of orthoclase from Colorado, a combination of the clino-pinakoid B, basal pinakoid C, prism m, clino-prism n, hemi-prisms $x = \{10\bar{1}\}$ and $y = \{20\bar{1}\}$.[1]

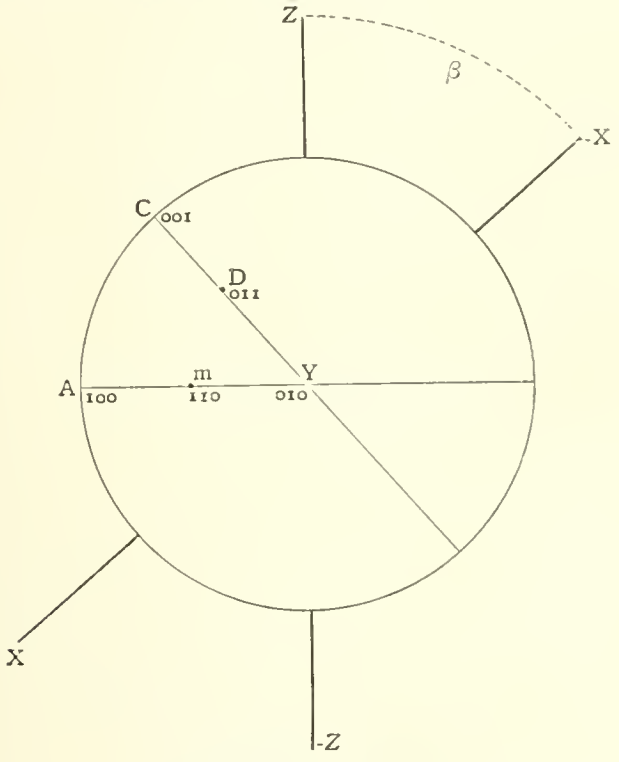


Fig. 211.—Monoclinic System.

49. **The Axial Ratios.**—The lengths of the axes are most conveniently obtained from the angles of two of the three parametral forms: the clino-prism (011), and the prism (1$\bar{1}$0) (Fig. 211).

Thus
$$\frac{a}{1}\cos mX = \frac{b}{1}\cos mY$$
$$\frac{a}{b} = \frac{\cos mY}{\cos mX}.$$

But $\cos mX = \cos Am \,.\, \cos AX = \cos Am \,.\, \sin AC$, from the right-angled triangle mAX, and

$$\cos mY = \sin Am, \text{ since } AB = 90^\circ$$
$$\therefore \frac{a}{b} = \frac{\tan Am}{\sin AC}$$

[1] For the two remaining Monoclinic Classes, see p. 281.

Similarly

$$\frac{c}{b} = \frac{\tan \mathrm{CD}}{\sin \mathrm{AC}}.$$

The acute angle between the axes XZ is always called β; the crystalline form is defined by the axial ratios $a : b : c$ and the axial angle β; the latter can often be found by direct measurement, since it is equal to the angle between the faces A and C.

Anorthic System

Crystals referable only to Three Unequal Oblique Axes and possessing no more than Centrosymmetry.

50. **The Anorthic System. Holosymmetric Class.**—The three axes in this system being not only unequal in length, but also inclined to each other at different angles, none of which is a right angle, the points X, Y, Z, at which the axes emerge from the sphere of projection cannot coincide with the poles of any faces upon the crystal (Fig. 212). Since there is

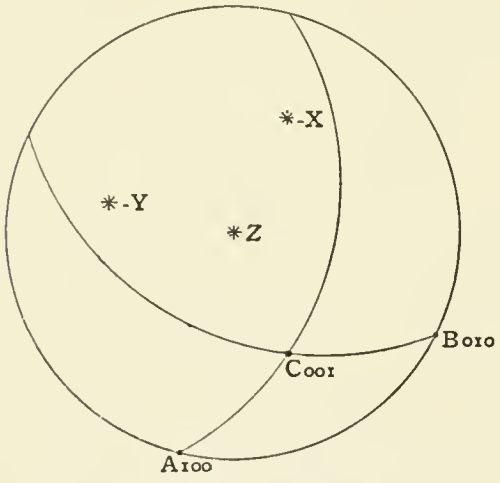


Fig. 212.—Method of Projecting the Anorthic System.

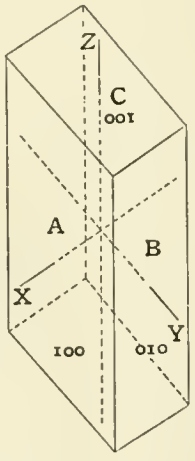


Fig. 213.—The Axial Pinakoids.

no plane of symmetry all the forms are pinakoids, consisting of a single pair of parallel faces. Three of these being arbitrarily chosen as {100}, {010} and {001} respectively, give by their intersections the directions of the axes (Fig. 213); the lengths of the axes are then determined by the positions, either of two faces which replace two of these edges (each therefore making intercepts upon only two axes), or of one face which replaces one of the corners (intersecting all the three axes). Pairs of forms parallel to the vertical axis are, as before, called prisms; the two lateral axes are distinguished as macro-diagonal and brachy-diagonal, and forms parallel to them, though really pinakoids, are usually called macro-domes and brachy-domes respectively; forms which inter-

sect all three axes (whose poles therefore lie inside any one of the triangles ABC, – ABC, etc.) are in the same way usually called pyramids.

The complete doubly oblique bipyramid which passes through all the

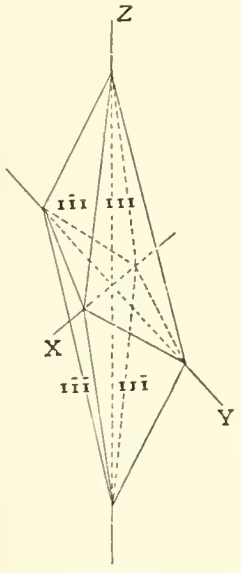


Fig. 214.—Anorthic Pyramid consisting of Four Pinakoids.

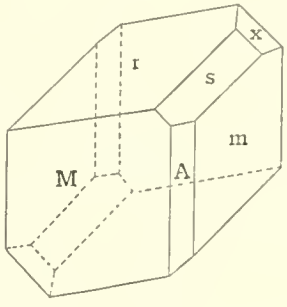


Fig. 215.—Axinite.

extremities of the three oblique axes consists in reality of four distinct pinakoid forms $\{111\}$ $\{11\bar{1}\}$ $\{1\bar{1}1\}$ $\{1\bar{1}\bar{1}\}$ (Fig. 214).

Fig. 215 represents a crystal of axinite from Dauphiné, a combination of the forms M$\{1\bar{1}0\}$, A$\{100\}$, $m\{110\}$, $r\{1\bar{1}1\}$, $s\{201\}$, $x\{111\}$.

51. **The Axial Ratios and Angles.**—In the anorthic system it is necessary to ascertain both the lengths and the directions of the three axes; there are therefore three axes, a, b, c, and also three axial angles, $\alpha = ZY$, $\beta = XZ$, $\gamma = XY$, to be determined. None of these can be found by direct measurement; they must all be calculated by five or more independent angles, as shown on p. 35; α, β, γ are the plane angles of Fig. 213.

In the preceding pages only those twenty-one classes have been described which are satisfactorily represented among minerals. In addition to these, the following eleven classes are also possible among crystals :—

Ditetragonal axis—polar	Tetragonal System.
Tetragonal axis—holoaxial and alternating	Tetragonal System.
Hexagonal axis—holoaxial and polar	Hexagonal System.
Ditrigonal axis—equatorial	Hexagonal System.
Trigonal axis—equatorial and polar	Hexagonal System.
Digonal axis—polar	Monoclinic System.
One plane of symmetry	Monoclinic System.
No symmetry	Anorthic System.

For a complete summary, see pp. 280-282.

CHAPTER II

THE REGULAR CONJUNCTION OF CRYSTALS

Some minerals are only found in Nature as isolated crystals, but the majority occur in groups which may be either regular or irregular; the irregular modes of grouping as described below are interlacing, radiating, etc. (see p. 240). The conjunction of two or more crystals is said to be regular when they are so united that certain parts of each are parallel to certain parts of its neighbour; two crystals so related may belong either to the same or to different species. There are three varieties of regular conjunction.

1. **Parallel Growth.**—In the first place, if *all* the parts (edges and faces) of one are parallel to all the corresponding parts of its neighbour, the two crystals are completely parallel. Except in the cubic system this is, of course, only possible for crystals of the same mineral; in the other systems different minerals have different interfacial angles and therefore cannot have all their parts parallel at the same time; in either the tetragonal or hexagonal system, however, two crystals of different minerals may conceivably be so united as to have all their *prism* faces parallel.

"Parallel growth," even on a very minute scale, may easily be recognised by the simultaneous reflection of the light from all the parallel faces of the group. One frequent instance of parallel growth is that afforded by crystals with "drusy" faces (see p. 249); each drusy face is covered with a number of minute crystals (so-called "sub-individuals"), which are generally parallel to each other and lie nearly in a plane. Drusy faces of this sort reflect light simultaneously from detached points all over their surface, that is, from the facets of the sub-individuals, and this gives rise to a peculiar velvety sheen, as may be well seen in the variety of göthite known as "sammet-blende" (from Przibram). It not infrequently happens that the crystals of a mineral are covered or partly covered with a later deposit of the same mineral, in which the more recent individuals, though parallel to the original crystals, are an entirely different combination of forms, owing perhaps to the fact that they have crystallised under changed conditions. In the so-called "nail-head spar" of Cumberland (Fig. 216), scalenohedra of calcite $\{20\bar{1}\}$ are terminated by rhombohedra whose cleavages are parallel to those of the scalenohedron, so that the two crystals are really parallel, although no extant

face of the one is parallel to any extant face of the other. Or, again, one crystal may simply differ from the other in the relative *size* of its faces. "Sceptre quartz" is the name given to thin prisms of quartz which are capped by stouter crystals, as is the case with some of the amethyst from Mursinka (Fig. 217). "Babel quartz" is a term applied to flat surfaces of that mineral found at Beeralston in Devonshire, which are formed by the predominance of one of the pyramid faces, and are covered with little triangular turrets of short parallel crystals.

A regular growth in which a number of sub-individuals are grouped so as to form a large crystal is called "polysynthetic"; thus large octahedra of fluor from several parts of Cornwall, notably the neighbourhood of Redruth, are drusy crystals built up by the polysynthetic growth of minute cubes all ranged in parallel positions (Fig. 393). Polysynthetic crystals show often, as in this instance, a different form or combination from

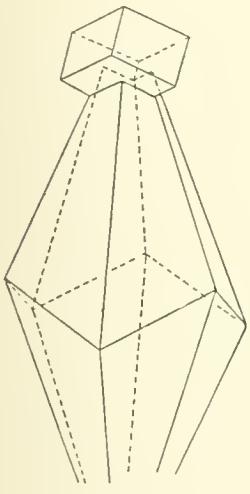


Fig. 216.—Calcite.

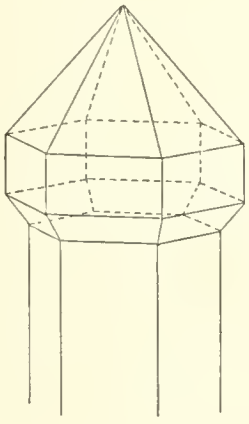


Fig. 217.—Sceptre Quartz.

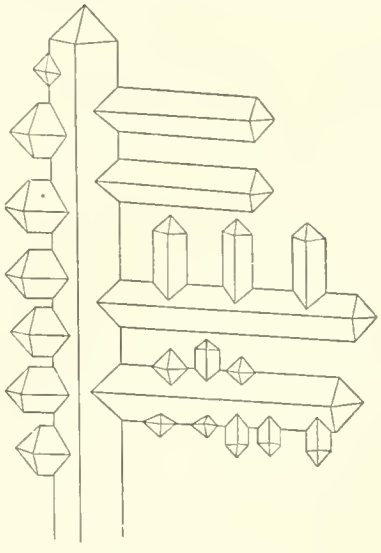


Fig. 218.—Copper.

that of their constituent crystals. A perfectly simple crystal is perhaps a thing of rare occurrence in Nature; the crystals of a mineral are often polysynthetic growths of several individuals in nearly parallel positions.

In Fig. 218 is represented a curious example of parallel growth illustrated by copper from Lake Superior, as described by E. S. Dana. Here the crystals are elongated combinations of the octahedron and dodecahedron extended along the different cube axes and grouped together in a "dendritic" or tree-like form. Dendritic growths—familiar in the frost patterns on window panes—are more usually due to the regular conjunction known as "twinning," described below in section 3.

2. **Regular Conjunction of Crystals which are not Parallel nor Twinned.**—If in a regular growth, whether of the same or of different minerals, the crystals are not completely parallel, they are partially so. In this case two crystals may be so united that (1) a face of one is parallel to a face of the other; that (2) an edge of one is parallel to an edge of the other; or that (3) a face and an edge of one are parallel respectively to a face and an edge of the other.

Thus (1) prisms of bournonite terminated by the basal plane are sometimes grouped together so that their terminations all fall into a single plane; (2) prisms of quartz from Switzerland are sometimes so united as to form a twisted or spiral group in which all the prism edges are nearly parallel; (3) crystals of the orthorhombic staurolite are sometimes affixed to the anorthic cyanite in such a way that the brachy-pinakoid of staurolite is parallel to the face (100) of cyanite, and the prism edges of the two minerals are at the same time parallel (Fig. 219).

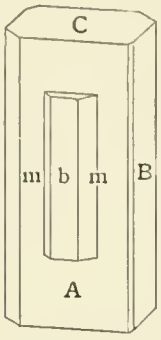


Fig. 219.—Staurolite on Cyanite.

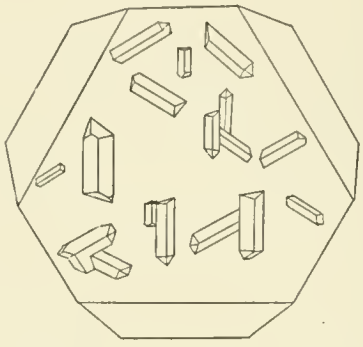


Fig. 220.—Rutile on Hæmatite.

Again, prisms of rutile (tetragonal) are found at several localities attached to plates of hæmatite (rhombohedral) in such a position that each prism lies with its face (100) upon the basal plane of the hæmatite, and has its prism edge perpendicular to the edge of combination (111):(100) of the hæmatite (Fig. 220). This third mode of grouping is the most common. It is found not only between crystals of different minerals, but between crystals of the same mineral. An instance is afforded by hydrargyllite, which crystallises in apparently hexagonal plates. These belong in reality to the monoclinic system and are a combination of C{001}, m{110}, A{100}; on specimens from Langesundfjörd two such crystals are sometimes so united that they have their basal planes C_1 C_2 parallel, and also the edge C_1 m_1 of the one parallel to the edge C_2 A_2 of the other (Fig. 221). In this instance the parallel planes on the two crystals are the same, but the parallel edges are different; such a growth is a transition towards the regular conjunction to be presently described as "twinning," in which both the parallel edges and the parallel faces are similar.

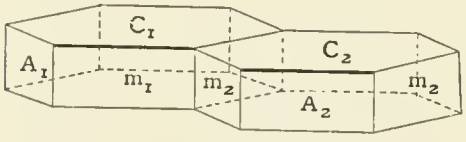


Fig. 221.—Hydrargillite.

"Drusiness" is sometimes produced by a regular deposit upon the faces of one mineral of minute sub-individuals belonging to a different species; thus tetrahedrite is very commonly covered with a drusy crust of crystalline chalcopyrite, due in all probability to a surface decomposition of the tetrahedrite. The well-known specimens from Herodsfoot Mine near Liskeard in Cornwall owe their beautiful colour to a tarnished crust of chalcopyrite, which also exhibits the velvety sheen mentioned above.

3. **Twinning.**—In the description of the different systems frequent

reference has been made to the planes and the axes of symmetry. It has been stated that the planes, edges, and corners of a single crystal are related in such a way that the similar parts may be obtained from each other either by reflection over the planes of symmetry or by rotation round axes of symmetry; further, that a plane of symmetry is always a possible plane of the crystal and that an axis of symmetry is always a possible edge of the crystal.

Now, among regular growths are found crystals resembling Figs. 223 and 224. Here, if A (Fig. 222) is an anorthic crystal in which none of the angles is a right angle, then A_1 is derived from A by reflection over the horizontal plane, and A_2 is derived from A by a rotation of 180° about the horizontal edge. In other words, if A_1 be reflected over the horizontal plane, or if A_2 receive a half turn about the horizontal edge, it is brought into a parallel position with A. In Fig. 223 the front faces make a re-entrant angle. In Fig. 224 they fall into one plane.

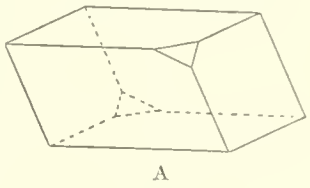


Fig. 222.

When two or more crystals are so united that one is symmetrical to the other about a plane which is a possible face on each, or about an axis

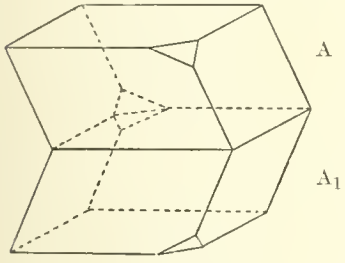


Fig. 223.—Twin Plane.

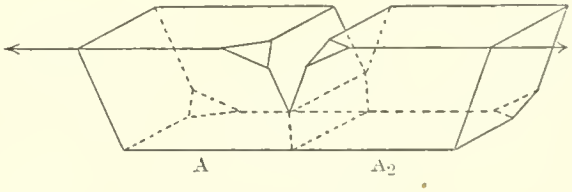


Fig. 224.—Twin Axis.

which is a possible edge on each, the crystals so united are said to be "twinned"; the plane of symmetry is called the "twin plane," and the axis of symmetry is called the "twin axis." Fig. 223 would be described as twinned about a face; Fig. 224 as twinned about an edge.

Fig. 225 is a twin of the gypsum crystal of Fig. 226, and may be described as twinned about the axis Z.

It was formerly the custom to describe all twins as obtained by "hemitropy," or rotation through 180°, about an axis which is called the twin axis, whether a possible edge or not, and to call the plane perpendicular thereto the twin plane, whether it be a possible face or not.

Since, however, a right and a left-handed crystal of quartz are sometimes twinned together so that they are symmetrical about a plane parallel to one of their faces, Fig. 237, and yet the one cannot be obtained from the other by a rotation, any more than a right-hand glove can be placed parallel to a left-hand glove, it is clearly impossible to describe all twins as due to hemitropy; again, an anorthic twin like that of Fig. 224 shows that there is not always a possible face of the crystal perpendicular to the twin axis.

The surface of union may either be a plane, or may be quite irregular.

If a plane, it is called the "composition plane," and in this case it is

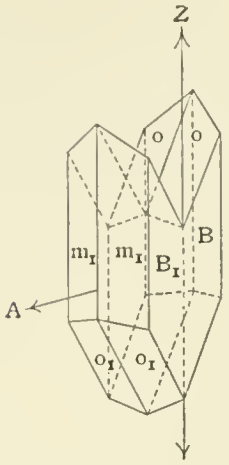


Fig. 225.—Gypsum.

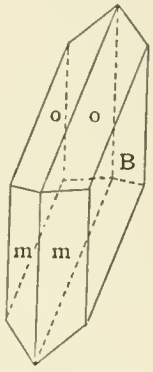


Fig. 226.—Gypsum.

generally parallel to the twin plane; in some instances it is parallel to the twin axis, and is sometimes some other face on the crystal which

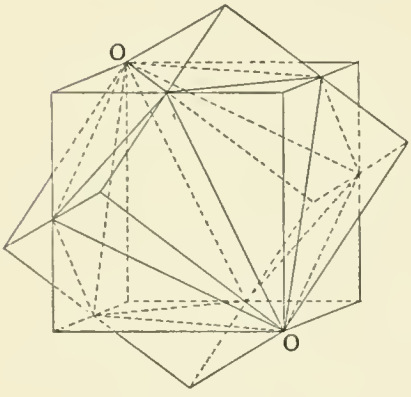


Fig. 227.—Interpenetration of Two Cubes.

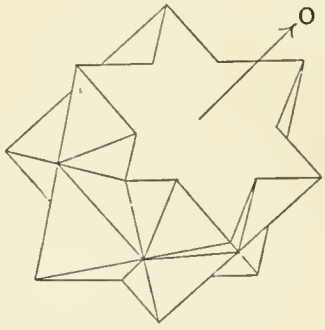


Fig. 228.—Interpenetration of Two Octahedra.

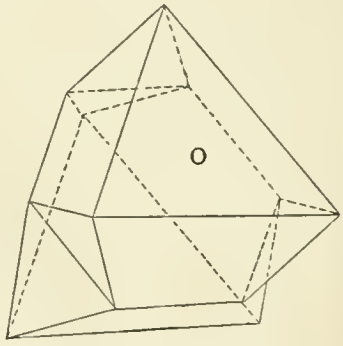


Fig. 229.—Juxtaposition of Two Octahedra; Spinel Twin.

is neither parallel nor perpendicular to the twin axis. The twin may either consist of two crystals placed side by side, as in Fig. 225, when it is called a "juxtaposition twin," or the two individuals may pass more or less completely through each other, when it is called an "interpenetration twin"; here there is no plane of composition.

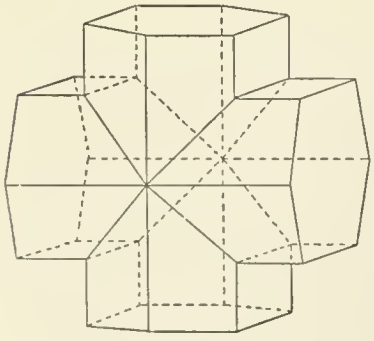


Fig. 230.—Staurolite.

Fig. 230 represents an interpenetration twin of the orthorhombic mineral staurolite, which receives its name from these cruciform growths.

Each of the two individuals is here a combination of basal pinakoid {001}, brachy-pinakoid {010} and prism {110}; the twin plane is a face of the brachy-prism {032} (cf. Fig. 640).

Fig. 227 represents an interpenetration twin of two cubes of fluor,

the twin axis being the cube diagonal OO which is common to them. Fig. 228 is an interpenetration twin of two octahedra united by the same law, O being the twin axis. These individuals might also be described as united by twinning upon the octahedron plane, to which that axis is perpendicular. Fig. 229 represents an octahedron twin in which the individuals are related to each other in the same way, but here union takes place along the octahedron face, and the crystals are best described as twinned upon that plane. This conjunction is so typical of spinel that it is often called the "spinel twin."

Twin crystals which have a twin axis may be called "rotation" twins, and those which have a twin plane may be called "reflection" twins.

A twin crystal may often be equally well described in more than one way; thus the crystal of gypsum (Fig. 225) may be described as due either to hemitropy about an axis A which is perpendicular to the ortho-pinakoid or about the vertical axis Z (the prism edge [B*m*]); this is an instance of the general truth that any crystal in which the twin axis is perpendicular to an axis of even symmetry may equally well be defined as due to hemitropy about an axis perpendicular to both these lines. In gypsum, however, since the plane of composition is also the ortho-pinakoid, the crystal is more appropriately defined as a reflection twin, twinned about that face.

The twin of Fig. 225 would be obtained by bisecting a simple crystal like Fig. 226 along a plane parallel to the ortho-pinakoid and rotating one half through 180°, while keeping the cut surfaces in contact; this is equally true of any juxtaposition twin which is capable of description as due to rotation, with composition perpendicular to the twin axis.

Most twin crystals, as in the above figures, betray their nature by their "re-entrant" angles, which give rise to notched, jagged, heart-shaped, knee-shaped, or arrow-headed forms very different from those of simple crystals; hence the terms "geniculated," and "macled," which are synonymous with "twinned." The French term "macle" is used by many authors instead of twin.

Twins which are completely interpenetrant are sometimes grown together in such a way as to be entirely devoid of re-entrant angles, so that to the eye they may appear simple crystals; the twin junction can then be only traced as a fine line traversing the crystal or by the different characters of the faces on either side of the junction. This is very strikingly exemplified by the interpenetration twins of quartz described on p. 370, where each pyramid face is dull in one part and bright in another, the dull part belonging to one crystal and the bright part to its neighbour.

It is evident that an axis of even (digonal, tetragonal, or hexagonal) symmetry in a crystal cannot play the part of a twin axis, for hemitropy about it would restore the crystal to its original aspect and would result in a parallel growth; neither, for the same reason, can any plane of symmetry in a crystal be the twin plane in a reflection twin.

4. **Supplementary Twinning.**—A very common mode of twinning is that in which a crystal belonging to one class is twinned about a plane

or an axis which is a plane or an axis of symmetry in another class of the same system. The introduction of the new element of symmetry in such cases may cause the twin crystal to possess the external symmetry of the holo-symmetric class.

Thus the upper hemimorphite crystal of Fig. 231, reflected over a

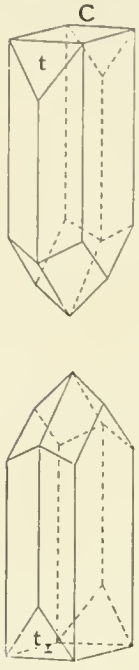


Fig. 231.

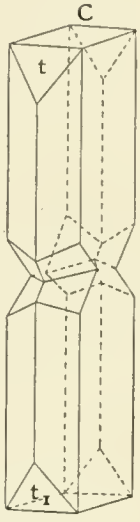


Fig. 232.

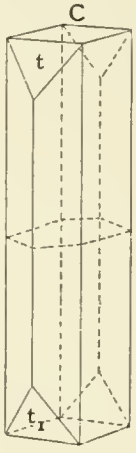


Fig. 233.

Figs. 231-233.—Supplementary Twinning of Hemimorphite.

plane parallel to the base C becomes the lower crystal; if these two are united along the twin plane, as in Fig. 232, the lower crystal supplies the faces t_1 of the supplementary dome $\{30\bar{1}\}$, which would be required to convert the dome $t\{301\}$ into a macro-prism of the holosymmetric class.

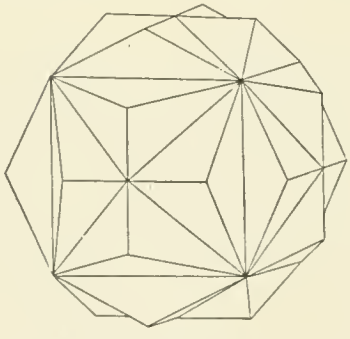


Fig. 234.—Supplementary Twin of Pyritohedra.

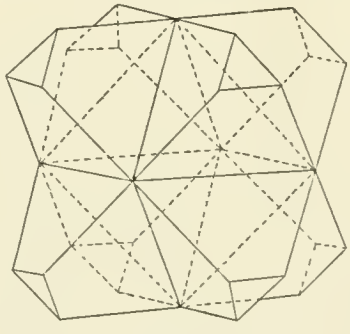


Fig. 235.—Supplementary Twin of Tetrahedra.

When there is a re-entrant angle, as in Fig. 232, the crystal is easily seen to be a twin; but when the two individuals unite as in Fig. 233, they present the aspect of a single individual in which, moreover, the two ends of the crystal cannot be distinguished, for they are actually bounded by faces of the same form. Such twins may be called "supplementary" twins.

Well-known examples of supplementary twinning are the interpenetrating pyritohedra of iron pyrites (Fig. 234) found at Minden in Prussia, and the interpenetrating tetrahedra of diamond (Fig. 235).

The faces of Fig. 234 make up the four-faced cube {210} of the holosymmetric class, and the supplementary tetrahedra of Fig. 235 make up the octahedron; for a projection of Fig. 234 would contain all the poles corresponding to the faces of Fig. 27, and the projection of Fig. 235 would contain all the octahedron poles.

Supplementary twins may be either juxtaposed or interpenetrating: in the latter case the twin may have the complete appearance of a holosymmetric crystal without re-entrant angles. Supplementary twins may be either rotational or reflectional, for the two supplementary forms, which have similar indices and make up a form of the holosymmetric class, may be related to each other either by repetition about an axis or

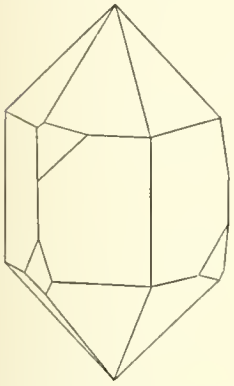


Fig. 236.—Left-handed Quartz.

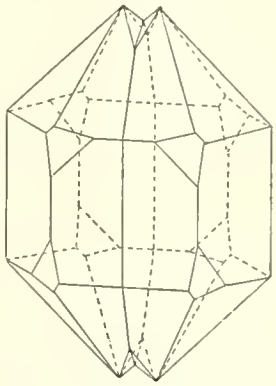


Fig. 237.—Brazilian Twin.

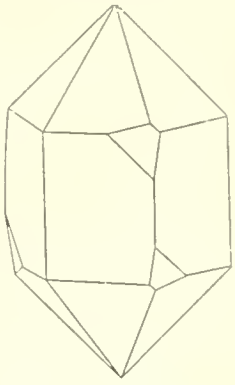


Fig. 238.—Right-handed Quartz.

a plane. Among the reflection twins the following remarkable case is especially noteworthy.

When a crystal belongs to a class which possesses neither plane of symmetry nor centre of symmetry its reflection in a mirror is, as was stated on p. 75, a totally different figure, just as the reflection of a right hand is a left hand. With such "enantiomorphous" crystals, therefore, a reflection twin is a union of a right-handed with a left-handed crystal.

The most characteristic examples of this sort of twinning are the so-called "Brazilian" twins of quartz (Fig. 237), which consist of a right-handed and left-handed crystal united sometimes along the plane of twinning (Fig. 237), but more usually by irregular interpenetration (Fig. 503).

When the supplementary crystals are enantiomorphous the twins cannot be described as merely rotational, since no hemitropy can bring a right-handed crystal (of quartz, for example) into complete parallelism with a left-handed crystal. The present case may be described either as due to twinning about the composition-plane, or as one of "alternating twinning," due to rotation about the vertical axis combined with reflection over the horizontal plane (see p. 371).

5. **Repeated Twinning.**—A very common mode of twinning among

minerals is that in which two crystals are twinned together, and then a third crystal is twinned according to the same law upon one of them, and then perhaps a fourth is twinned upon the third, and so on (Figs. 239-241).

This twin grouping may take place in two ways :—

(1) The twin plane or twin axis for individuals II and III, though belonging to the same form as that which unites II and I, may be a different face or edge of the form. This "repetition with inclined twin planes" leads to a cyclical grouping, as in Fig. 240, where the prism face m_1 which unites II with I is not parallel to the prism face m_3 which unites it with III. Sometimes the repetition even leads to a completely closed chain of individuals.

(2) The twin plane or axis which unites II with III may be parallel to that which unites II with I.

Now it is evident that two successive half turns about the same line are equivalent to a whole turn, and restore the crystal to its original

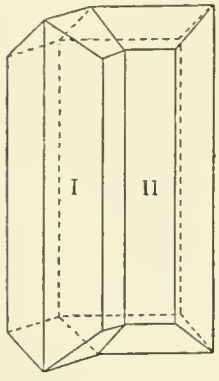


Fig. 239.—Aragonite Twin.

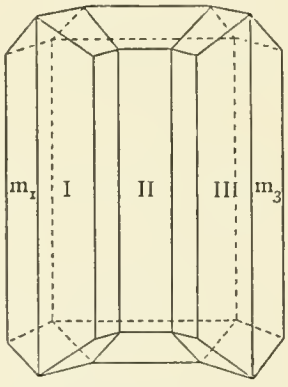


Fig. 240.—Inclined Twin Planes.

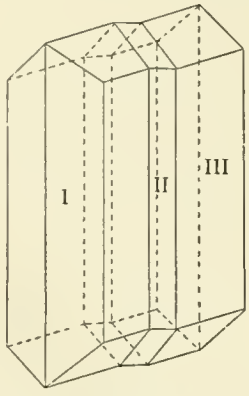


Fig. 241.—Parallel Twin Planes.

position, and that two successive reflections about the same plane have the same effect. In this case, therefore, III will be parallel to I, and II will appear to be interposed in twin position between two portions of the same crystal (Fig. 241).

If twinning upon a pinakoid form be repeated, it is clear that the second mode of grouping is the only one possible, for the form does not comprise any inclined faces.

Twin Lamellæ.—Juxtaposed twin crystals show a curious tendency to become tabular parallel to the plane of twinning.

This is often exhibited in a remarkable manner by twins which are repeated with parallel twin planes. Thus the interposed crystal II in Fig. 241 may be reduced to the thickness of a mere plate or twin lamella.

When the twinning is repeated a number of times with parallel twin planes and the lamellæ are sufficiently thin, as in the albite of Fig. 243, which exhibits merely a repetition of the twinning of Fig. 242, the crystal may appear to be a single individual traversed by a series of fine lines, the so-called "twin striæ," parallel to the plane of twinning. Fig.

244 represents a crystal of albite whose basal plane C and the hemi-prism $x\{101\}$ are traversed by twin striæ all parallel to the pinakoid B. Fig. 244, if magnified, would present the appearance of Fig. 243. In albite

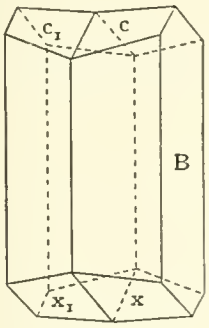


Fig. 242.—Albite Twin.

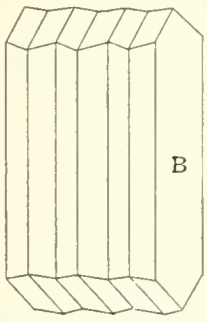


Fig. 243.—Twin Lamellæ.

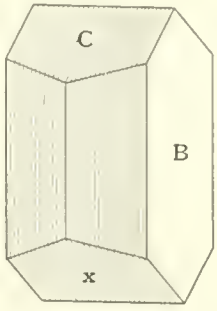


Fig. 244.—Twin Striations.

the twin plane is B(010), which, since the mineral is anorthic, is not perpendicular to C or to x.

6. **Mimetic Twinning and Pseudo-symmetry.**—In the supplementary twins described above, the planes and axes of twinning would be planes and axes of actual symmetry in some other class of the system to which the crystals belong, and the faces of each crystal, after twinning, occupy the positions of possible faces on its neighbour and would have rational indices if referred to its axes. The two individuals, if completely interpenetrating, may then appear to constitute a single crystal. The result of such twinning is therefore to apparently invest the crystal with a higher degree of symmetry than it really possesses, and to transfer it from one class to a *class* of higher symmetry within the same system.

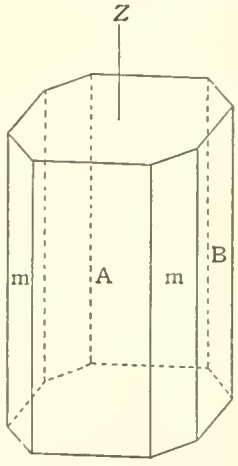


Fig. 245.—Pseudo-tetragonal Axis.

Another and similar result which may be brought about by twinning is that in which a crystal actually appears to belong to another *system* of higher symmetry than its own. In every system are to be found certain minerals which approximate very closely to the geometrical symmetry of a more symmetrical system; an orthorhombic crystal, for example, whose horizontal axes are very nearly equal, will approximate to the geometrical symmetry of a tetragonal crystal and will have a prism angle of very nearly 90°; in such a crystal the vertical axis will be very nearly a ditetragonal axis instead of one of twofold symmetry, and planes parallel to the faces of the prism $\{110\}$ will be very nearly planes of symmetry (Fig. 245). Twinning about the prism faces would have the effect of making the crystal still more nearly tetragonal, since it would make these faces actual planes of symmetry in the twin, and would cause the faces of the different forms to be so repeated as to satisfy the symmetry of the tetragonal system; a "pseudo-tetragonal" crystal so twinned by interpenetration might be externally indistinguishable from a tetragonal crystal. In this way a crystal may simulate the symmetry of a higher

system; such twinning is called "mimetic," or imitative, and crystals so twinned are said to be "pseudo-symmetric."

A familiar example is afforded by the orthorhombic mineral aragonite. The prism angle in this mineral is near 60° (actually 63° 48′); consequently a combination of the prism {110} with the brachy-pinakoid {010} is nearly a hexagonal prism; and planes parallel to the prism faces are planes of pseudo-symmetry; these are also the common planes of twinning, as shown in Figs. 240, 241.

If each face of the prism form becomes a twin plane, the triplet so formed will have three new symmetry planes inclined nearly at 60° to each other, and will approximate even more closely than the simple crystal or the twin to the symmetry of the hexagonal system; three individuals so twinned will present almost exactly the aspect of a hexagonal prism.

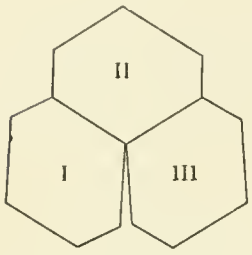


Fig. 246.

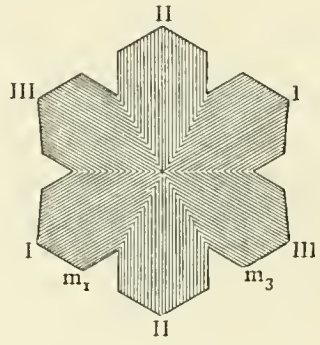


Fig. 247.

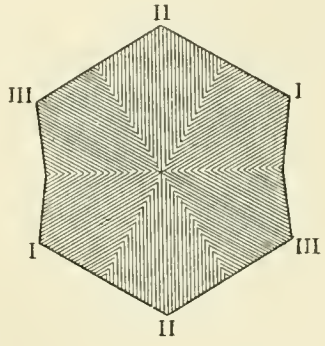


Fig. 248.

Figs. 246-248.—Aragonite Triplets.

Since the prism angle is not quite 60° the faces of I and of III do not quite coincide (Fig. 246) and a re-entrant angle betrays the nature of the twin.

More frequently mimetic twin groups are not juxtaposed but interpenetrant, and in such cases the pseudo-symmetry is even more complete.

Thus in the interpenetrant triplet of aragonite (Fig. 247), m_1 is the twin plane for I and II, m_3 for II and III.

The crystals may completely interpenetrate, as in Fig. 248, and may be almost indistinguishable from a simple hexagonal crystal. Generally, however, striations on the basal pinakoid which, in each individual, run parallel to the brachy-pinakoid, render it possible to distinguish the various individuals of the group.

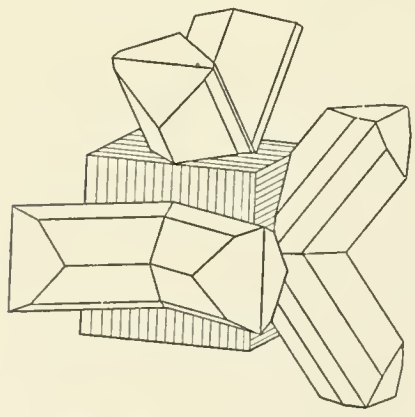


Fig. 249.—Marcasite Twins on Pyrites.

In Fig. 249 is represented a remarkable example of twinning, combined with the regular conjunction of one mineral upon another, as described by Trechmann from Brilon in Westphalia. The cube is iron pyrites; the other crystals are twins of marcasite (the ortho-

rhombic modification of iron disulphide); they are combinations of macroprisms {101} and {104}, terminated by the prism {110}, each twinned on a face of {110}, and each cube face of the pyrites bears a marcasite twin having its twin plane perpendicular to the cube face and parallel to the striations upon it.

7. **Secondary Twinning.**—It was discovered by Reusch and Baumhauer that when the blade of a knife is pressed into a cleavage rhombohedron of calcite across one of the terminal edges (at *b*), a slight sideward pressure being at the same time given to the blade towards the summit of the rhombohedron, the following remarkable effect is produced:—as the knife enters the crystal, successive layers, all parallel to the plane *cde*, which would truncate the rhombohedron edge, glide along each other; this gliding takes place exactly so far that a portion of the crystal extending to the depth cut by the knife takes up a new position and constitutes a new crystal twinned upon the original rhombohedron by reflection over *cde*, the face (011). This is shown in Figs. 250, 251,

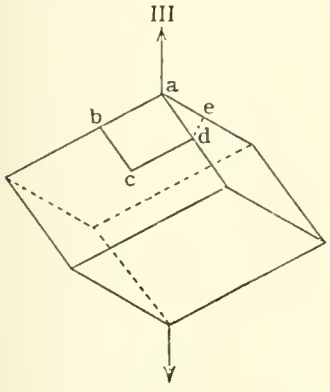


Fig. 250.

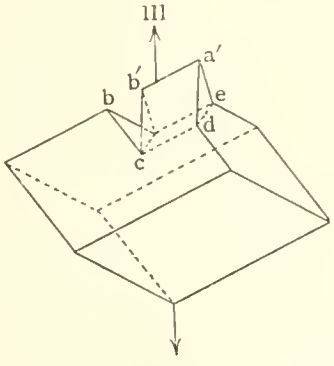


Fig. 251.

Figs. 250, 251.—Baumhauer's Experiment.

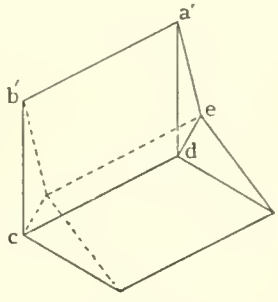


Fig. 252.—Calcite twinned on (011).

where *a′b′cde* is the position adopted by the portion *abcde* of the crystal between the knife and the summit *a*.

The plane (011) along which this gliding takes place is called a "glide-plane," and it becomes after the operation a plane of "secondary" twinning, as contrasted with ordinary twinning which has taken place during the growth of a crystal.

A complete twin of this sort—such as is sometimes found in nature as an ordinary twin—is shown in Fig. 252.

It will be observed that the summit of the crystal was at *a* and is now at *b′*, and the direction *ba* is reversed in *a′b′*, the obtuse angle *a* being converted into an acute angle *a′*.

Glide-planes have now been observed on many minerals; in most of them they are parallel to planes of cleavage.

CHAPTER III

VICINAL FACES

1. **Vicinal Faces.**—It has been stated above that the faces of a crystal are such as possess simple rational indices. But many crystals have bright plane surfaces which cannot be referred to simple indices; these are by no means to be ignored or ascribed to irregularity of growth; they are symmetrical in accordance with the symmetry of the crystal and replace the simple forms which would have low indices; thus, for example, cubes of fluor-spar are generally found, when closely examined, to be in reality four-faced cubes; each apparent cube face consists of a very flat square pyramid nearly coincident with the cube (Fig. 254). The vicinal faces are of considerable importance in determining the true symmetry of a crystal, for they generally belong, not to the simplest possible forms, which are perpendicular to the planes and axes of symmetry, but to some more complex form capable of indicating the class to which the crystal belongs. When they replace a face which is perpendicular to an axis or a plane of symmetry they can be easily detected by virtue of their repetition; thus a vicinal form replacing the cube in the holosymmetric class must consist of a flat four- or eight-faced pyramid (Fig. 254); one replacing the octahedron must consist of a three- or six-faced pyramid (Fig. 259); the edges between the vicinal planes and their slight salient angles can generally be observed though the faces be inclined to one another at very small angles, not exceeding a few minutes.

The vicinal faces of a single crystal must not be confused with the faces which are often met with on *pseudo-symmetric* crystals, where the simple forms belonging to the different constituent crystals meet at very small angles.

Thus an apparent cube may in reality consist of twelve monoclinic individuals, each having the form of the wedge OABCD, so united that their apices meet in O, the centre of the cube (Fig. 253). If the faces CBD, ABD are respectively the basal pinakoid {001} and the ortho-pinakoid {100} of the monoclinic individual, the angle between them may be slightly less than 90°; the four faces, such as ABD, which constitute an apparent cube face will in this case not fall exactly into a plane but will constitute a low four-sided pyramid.

A similar figure may be due, as in fluor, to vicinal faces belonging to a four-faced cube (Fig. 254), which replace all the faces of a *single*

cube; but whereas the pseudo-symmetric crystals will have a constant angle over the cube edges, namely the angle belonging to the monoclinic individuals, the vicinal faces of the single cube may belong to different forms in different crystals of the mineral and vary from one crystal to another. It may conceivably happen also that the faces in a pseudo-symmetric crystal are also themselves vicinal faces; the distinction will then be more difficult.

Vicinal faces are very often developed in interpenetrant twin crystals where one individual emerges through the other.

One of the most conspicuous and common examples is fluor-spar, whose crystals are usually the interpenetrant cubes of Fig. 255; in these it will generally be found that the cube faces through which a corner of the interpenetrating crystal protrudes are replaced by the facets of a flat four-faced cube, as indicated by the shading (cf. Fig. 436).

Experiments upon crystals grown in the laboratory show that vicinal faces vary during the growth of the crystal—at one moment having one

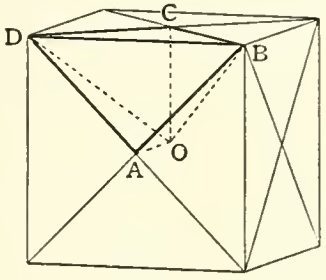


Fig. 253.—Pseudo-symmetric Cube.

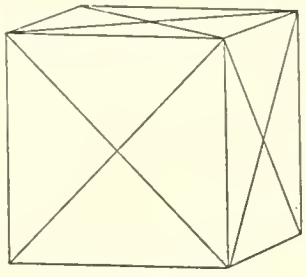


Fig. 254.—Vicinal Faces replacing Cube.

set of indices, and at another moment another; they vary possibly with the concentration of the solution or the rate at which they are growing.

The crystals of natural minerals, which grow, doubtless, under very variable conditions, constantly exhibit vicinal faces; these are very near to the faces of simple forms, and therefore possess very high indices. Their interest and importance consist in the fact that, whatever be their indices, the number of the facets corresponds to the symmetry of the crystal, and they are therefore most valuable aids in determining the class to which it belongs. One way in which this property is employed is the following.

2. **Light Figures.**—It was observed by Brewster that when a distant source of light, for example a candle flame, is observed by reflection in a crystal face held close to the eye, the image may be, not a sharply defined one, but blurred in such a way as to give a curiously regular geometrical star. Further, that the symmetry of this star is precisely the symmetry of the reflecting face.

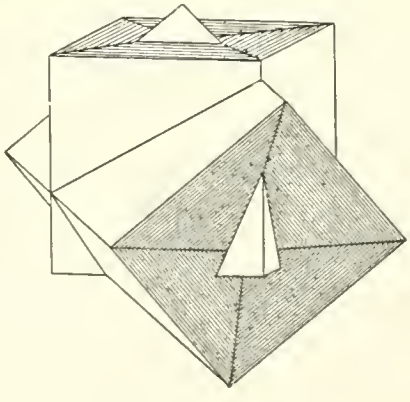


Fig. 255.—Fluor-spar.

It is easy to understand from what has been said above that such

images, to which Brewster gave the name of "light figures," will be produced by vicinal faces.

A perfectly plane reflecting surface will give a single clear image of a small circular spot of light, but a cube face such as that of fluor, which consists of four vicinal faces, as in Fig. 254, will give four such images which are extremely close to each other, since the four reflecting surfaces

Fig. 256.

Fig. 257.

Figs. 256, 257.—Light figures from Fluor.

are nearly coincident (Fig. 256). If there are a number of vicinal faces lying in the four zones of the cube edge, *i.e.* a number of consecutive four-faced cubes $\{hk0\}$, the image will be converted into a hazy four-rayed star (Fig. 257).

The image given by any face of an octahedron of common alum is a three-rayed star, as in Fig. 258. This is due to the fact that the

Fig. 258.—Light figure from face of Alum.

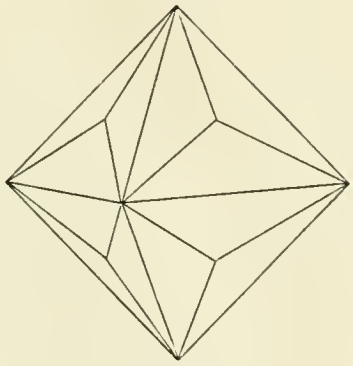


Fig. 259.—Alum.

apparent octahedron of alum is in reality a very flat three-faced octahedron (Fig. 259), whose facets nearly coincide with the octahedron faces.

The images reflected from a crystal which has been acted upon by a solvent are almost always of this composite nature, for the reason explained below on p. 114.

CHAPTER IV

THE MEASUREMENT OF CRYSTALS

We are now equipped with nearly all that is necessary for the complete description of the "crystalline form" of any mineral. If the angles between the faces of a simple crystal can be measured, their poles may be plotted out on a projection; the planes and axes of symmetry will then reveal themselves, and, according to its symmetry, the crystal can be referred to one of the six systems, and to one or other of the classes within that system, due regard being paid to the physical features of the faces as well as to the angles which they make with one another.

Three faces are chosen as "axial planes," which by their mutual intersections give the directions of the axes; in the Anorthic system any three planes may be selected; in the other systems they must be chosen in accordance with the symmetry, as has been explained above on p. 38. A fourth face which intersects all three axes is then chosen as "parametral plane" to determine the lengths of the axes, these lengths being calculated from the equations on p. 35; or two planes, each of which cuts two axes and is parallel to the third, may be used for the same purpose. The indices of the remaining faces of the crystal are then determined by their zone relations.

But to make any such description possible it is necessary to measure the angles between the faces; this is done by means of the instrument known as the **goniometer**. Of this instrument there are two sorts: (1) the contact goniometer, and (2) the reflecting goniometer. The former was the contrivance used by Romé de l'Isle and Haüy, the French crystallographers who first measured crystals with accuracy, and is still employed for large dull crystals whose faces are not smooth enough to yield reflections of a distant object; but for all accurate measurements it has been supplanted by the reflecting goniometer invented by Wollaston in 1809.

1. **The Contact Goniometer.** — The contact goniometer consists simply of two straight metallic bars hinged together by a pivot, and fitted to a graduated semicircular arc whose centre coincides with that of the pivot (Fig. 260).

To measure the angle between two faces A and B, the arms are adjusted until one is in contact with the face A, and the other with the face B; to ensure close contact the crystal is held up to the light and

viewed along the edge between A and B, and the arms are moved about the pivot until no light passes between them and the faces, care being taken that the plane containing the arms is perpendicular to the edge. One arm is usually fixed so as to coincide with the zero division on the scale.

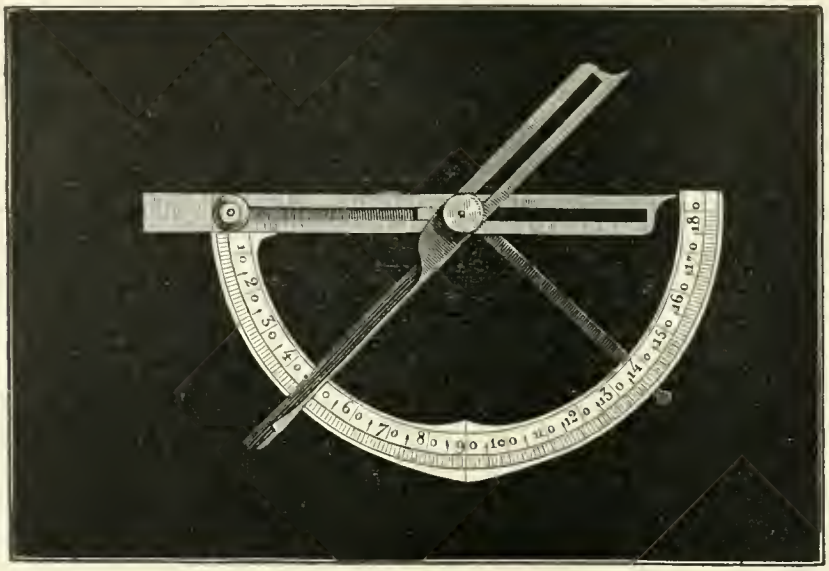


Fig 260.—Contact Goniometer.[1]

Sometimes the two arms and their pivot are so made that they can be removed from the scale and adjusted by themselves, and then replaced upon the scale in order to determine the angle.

2. **The Reflecting Goniometer.**—The reflecting goniometer is an instrument of far greater precision and delicacy and is universally employed when small crystals with bright faces are available; its principle is as follows:—

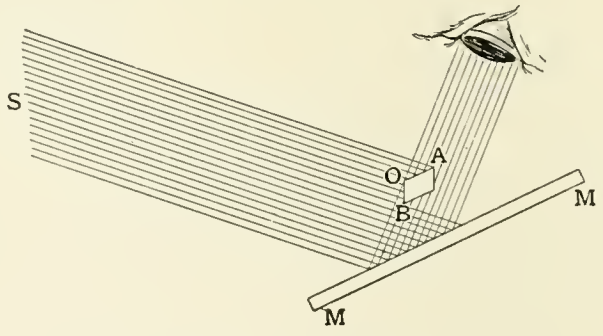


Fig. 261.—Principle of Reflecting Goniometer.

Let M (Fig. 261) be a fixed mirror in which is viewed the image of a bright signal S, such as a horizontal slit cut in a window shutter, at a distance of 20 feet or more from the mirror.

Let OA, OB be two bright faces of a small crystal, and let their edge

[1] Fig. 260 is reproduced from a photograph of an instrument, exactly like Haüy's own goniometer, presented to Professor Buckland by the Duke of Buckingham in 1824, and now in the Oxford Museum.

O be parallel to the mirror. The crystal is first so placed that the image of S as seen by reflection from OA exactly coincides with the image reflected in M; this is easily effected if the crystal is a small one, since the two images can then enter the eye at the same time. The crystal is then turned about its edge O until the image of S seen in OB exactly coincides with the image reflected in M; and the angle α through which it has been turned is registered. Let a, b be normals to the two crystal faces; it is evident that in the second observation the face OB occupies the exact position which the face OA had in the first observation, hence b has been turned into the position of a, and the angle α (Fig. 56) must be the angle between the normals a, b. But this is the very angle which is taken in crystallography to measure the inclination of the two faces

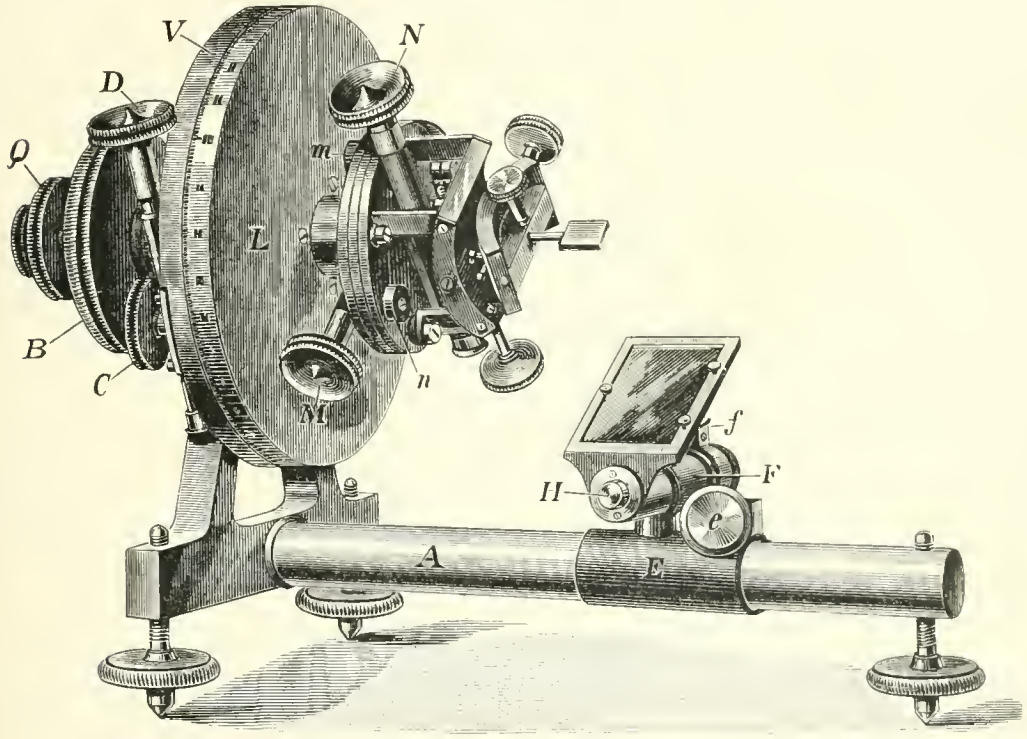


Fig. 262.—Reflecting Goniometer.

(see p. 31). The measurement of the normal angle is therefore made directly by means of the reflecting goniometer.

To apply the above principle the necessary requirements are (1) a graduated circle upon the axle of which the crystal is fixed; (2) means for making the edge O coincide with the axis of the circle so that the crystal may be turned about its edge; (3) means for setting the mirror parallel to the axis.

In the goniometer (Fig. 262), L is the graduated circle, having a scale divided to half degrees, which is turned by the milled head B, and a vernier upon the fixed disc V permits readings to be made accurately to one minute.

The mirror may be fixed at any distance from the circle and at any

required inclination by sliding or rotating the tube E on the bar A. E is clamped by the screw *e*; the mirror, after being adjusted parallel to the axis of the instrument by the tube F, is clamped by means of the screw H.

The crystal is fastened by a mixture of bees'-wax and pitch to the small brass pin with a flat square head shown affixed to the crystal carrier MN; the latter is a contrivance for "centring" and "adjusting"; the two screws M and N are used to move the crystal in the directions of their length until it occupies a central position exactly on the axis, and does not leave that position when the circle is rotated. In front of these are two smaller screws at right angles to each other, which set in motion two portions of cylindrical arcs of which the crystal occupies the centre; these are used to adjust the edge of the crystal until it is parallel to the axis. After the crystal has in this way been properly centred and adjusted, it rotates about its own centre when the graduated circle is turned, and it is then ready for the measurement of the angle between the two faces which meet in the adjusted edge.

C is the clamp for the circle, and D is the fine-adjustment.

The manner in which the goniometer is actually used is shown in Fig. 263. This figure represents a simple form of the instrument in which the crystal-holder is practically the same as that used by Wollaston in his original goniometer. In place of the cylindrical arcs and tangent screws of Fig. 262 are two rods at right angles to each other, supplied with milled heads, by which they can be rotated in their bearings; these rods, to one of which the crystal is fixed, constitute two axes by means of which the crystal edge is adjusted. The crystal is centred by means of the L-shaped bar which carries the adjustment piece; this bar is shifted upon the goniometer disc until the crystal is on the axis of the instrument, and is then clamped to the disc.

In order to make the image of the signal seen in the crystal exactly coincide with that seen in the mirror, it is convenient to introduce in front of the mirror a small card screen just high enough to intercept the light which falls from the signal upon the mirror, but not that which falls upon the crystal; the screen having been moved sideways until it cuts off half the image of the horizontal signal-slit as seen in the mirror, the crystal is turned until the image seen in its face exactly forms a prolongation of the half image seen in the mirror. The position of the scale is then read by means of the vernier.

A great advantage of the reflecting goniometer is due to the fact that when once two faces of a crystal have been correctly adjusted, so that during a rotation of the circle the images reflected by these two faces come in succession into their proper position, the edge about which the crystal turns is not only the edge in which the two faces intersect, but is parallel to the axis of their zone. *All* the faces in the zone must therefore also give correctly adjusted images in succession, and all the angles belonging to that zone can be measured during a single rotation of the divided circle.

Even without making any angular measurements the observer may thus, by a single rotation of the crystal, quickly identify all the faces which belong to a zone.

The examination of a crystal by the reflecting goniometer consists in the adjustment and measurement of one zone after another. In any zone the reading of the scale for each successive face is noted, and the angle between any two faces is simply the difference between their two readings.

In viewing the images the eye is placed at such distance from the

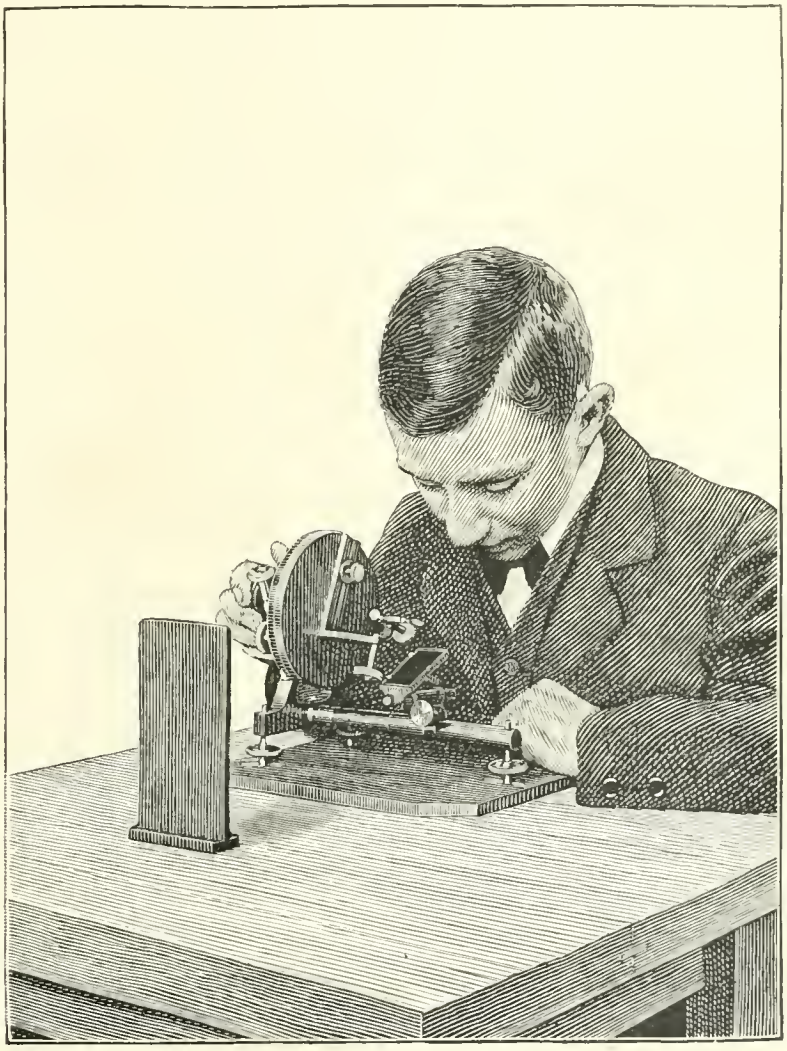


Fig. 263.—Crystal measurement.

crystal, that it easily takes in at the same time the reflections both from the crystal and the mirror.

Before adjusting a zone it is advisable to mount the crystal upon its holder in such a position that the zone axis is approximately parallel to the axis of the instrument, and a prominent face of the zone is parallel to one of the tangent screws which move the two cylindrical arcs, and perpendicular to the other (or, in Fig. 263, parallel to the smaller adjusting

rod). This face is first adjusted by the tangent screw to which it is perpendicular, then a second face in the zone is adjusted by the second tangent screw; the graduated circle is turned back to its original position, and the first face re-adjusted by the first screw. After a few repetitions of this process, both faces, and therefore the whole zone, will be found to be in adjustment.

It is necessary to have a signal situated at a considerable distance from the goniometer, so as to avoid the error due to imperfect centring of each edge of the zone. The greater the distance of the signal the more nearly parallel are the two beams SA, SM in Fig. 261. In order to save space a very convenient plan is to have for signal a small slit situated at the principal focus of a large lens placed between the slit and the mirror; the rays of light which diverge from the slit and fall upon the lens issue from the lens as parallel rays, and are equivalent to rays from a signal placed at an infinite distance from the instrument. The slit may be illuminated by a lamp placed behind it.

By means of the reflecting goniometer the angles of even the smallest crystal may be measured with perfect accuracy, provided that its faces are sufficiently smooth and bright to yield reflections of the signal.

The Telescope-Goniometer.—For greater convenience and for more refined work upon very good crystals, goniometers are made in which the graduated circle is horizontal and its axis vertical. The signal is a small slit illuminated by a lamp, and is placed at the focus of a lens which is situated near to the crystal; the lens and slit constitute a *collimator*. The mirror is abolished and the observations are made with a telescope furnished with cross wires in the eye-piece; each face is then adjusted until the image of the collimator slit reflected by the face exactly coincides with the cross wires of the telescope. A convenient form of slit is that shown in Fig. 264, which represents the reflected image of the signal as viewed by the telescope and adjusted upon the cross wires.

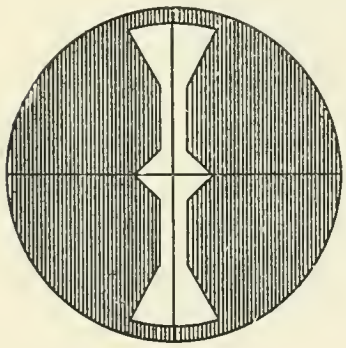


Fig. 264.—The Signal.

By means of an auxiliary lens placed in front of the object-glass the telescope may be converted at will into a microscope, so that the crystal may be adjusted and examined.

In Fig. 265 the left-hand tube is the collimator and the right-hand tube the observing telescope; of the three milled heads at the lower part of the instrument the lowest serves to raise or depress the crystal-holder; the next, to rotate the crystal-holder during adjustment; the upper one, to rotate the graduated disc during measurement.

The scale is read by a small lens shown in the figure.

The telescope is represented with the auxiliary lens placed before the object-glass for the purpose of viewing the crystal. By swinging back the sliding bar which carries this lens another lens is brought in front of the eye-piece; this serves to identify the facet which reflects the image seen in the telescope, for when the lens is close to the eye-piece the

image is seen, and as it is withdrawn gradually from the eye-piece the facet becomes visible.

The telescope-goniometer can also be used as a spectrometer, to measure the refractive indices of a mineral by means of a refracting prism.

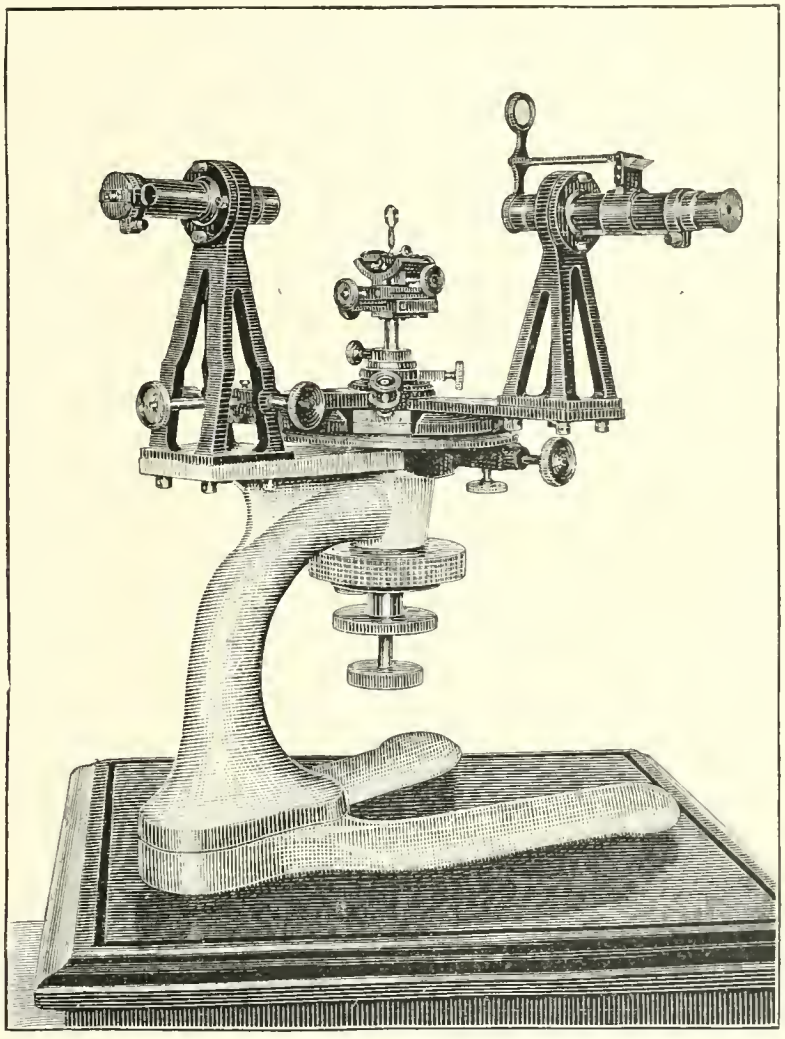


Fig. 265.—The Telescope-Goniometer.

The Theodolite Goniometer.—In this instrument, which is now rapidly coming into use, the crystal-holder is mounted on a vertical disc, like Fig. 262, which is itself mounted on a goniometer, like Fig. 265. It is not then necessary to readjust the crystal for each zone, but two readings are taken for every face, one upon each circle, and the greater part of the crystal is measured without removing it from the holder.

The Three-circle Goniometer.—This instrument possesses a third disc, so that each zone can be adjusted by two of them, and measured by the third, without removing the crystal.

From what has been said above it is evident that the *symmetry* of the reflected image will often indicate the symmetry of the faces. Vicinal

faces, whether produced by the natural growth of the crystal or by subsequent etching, will give multiple images. A face which is perpendicular to an axis of trigonal symmetry will therefore generally give a triradiate star, if the signal be a small one; one which is perpendicular to an axis of tetragonal symmetry will give a star-shaped reflection having four rays. It is therefore of great importance to note the character of the image yielded by each face of a crystal, both as regards its sharpness and its symmetry. More importance is to be attached to sharply defined single images than to multiple images or such as are blurred.

CHAPTER V

THE PHYSICAL PROPERTIES CHARACTERISTIC OF CRYSTALS

On the Relation between Physical Properties and Form

From the physical point of view a crystal is very different from the unerystallised substance, just as a regiment is a very different thing from a crowd of men; the material may be the same, but it is differently arranged. When a crystal is subjected to any physical action the resulting effects depend not only upon the magnitude and nature of the action, but also upon the direction in which it is applied.

The crystal may, for example, be more elastic in one direction than in another; its behaviour is therefore different according to the direction in which pressure or flexure is applied; or, again, the action of the crystal upon radiant energy, such as light, is different according to the direction in which the light is transmitted: it may be more opaque or more deeply coloured in one direction than in another; or, again, the crystal when heated may expand unequally in different directions, indicating that its behaviour is different in different directions even when it is uniformly subjected to the same action. These facts point to a certain regular arrangement of the particles, owing to which the properties of the crystal along any parallel lines of particles are constant, but different from those along other lines of particles inclined to the first, just as in a military square the disposition of the men is the same along parallel lines, but different along different directions.

Now the external form of the crystal is doubtless also due to the internal arrangement of its particles, and we have found the external form to be governed by certain simple laws of symmetry, according to which certain parts of the crystal are repeated, and certain directions in the crystal are similar to each other.

It is not surprising, therefore, that the same general laws of symmetry are found to govern the physical characters. This we have already seen to be the case with the cohesion, as indicated by the property of cleavage. When cleavage takes place along any one plane it can also be obtained with equal facility along all the planes belonging to the same "form"; that is to say, the directions of least cohesion are symmetrical direc-

tions in the crystal, and are repeated over the planes of symmetry and round the axes of symmetry. This is equally true of all the physical characters.

All lines in the crystal which are similar in the geometrical sense are also lines along which the physical characters are the same, and the planes and axes of symmetry are planes and axes of symmetry both for the geometrical and the physical features.

To establish the truth of this extremely important law, many careful measurements have been made of properties which are otherwise of little practical value for the purpose of determining the systems of minerals, or of identifying species; such are the comparative measurements of the elasticity, cohesion, and expansion of crystals; of their conductivity for heat and electricity; of their magnetic properties and dielectric constants; these are for the most part omitted here as belonging more properly to physical crystallography.

One class of characters in particular is of the greatest theoretical importance, and is at the same time so easy of application that it has become one of the most subtle and yet the most facile means of determining the symmetry of crystals and of identifying species, even when the crystalline form is not available; namely, the group of phenomena known as the *optical characters*, which merit a detailed study on the part of every student of mineralogy.

Before describing the optical characters we may illustrate the connection between the symmetry of form and structure by a brief reference to certain experiments upon the elasticity, cohesion, and some other properties of crystals.

1. **Elasticity.**—The elasticity of a substance in any direction is determined by the elongation produced in a bar of known length and unit sectional area under the action of a known force, the bar being cut so that its length coincides with the required direction.

Experiments have been made upon crystals to determine the elasticity by the amount of flexure produced in a plate of given dimensions under the action of a given weight. For this purpose a slice cut out of the crystal in a given direction is supported on two knife edges, whose distance from each other can be accurately measured; the length, breadth, and thickness of the slice are determined by microscopical measurements; it is then subjected to the action of a weight suspended by a knife edge, which rests upon the slice midway between the supports. The extent to which the plate is bent is measured by delicate mechanical or optical means, and from these data the "co-efficient of elasticity" may be calculated.

Experiments of this nature have been made upon crystals belonging to the cubic, hexagonal and orthorhombic systems, and have proved that the elasticity is always the same along directions which are symmetrical to each other with regard to the symmetry planes of those systems.

If lines were drawn in all directions from any point within a crystal, each line representing by its length the elasticity in its direction, their extremities would form an "elasticity surface," which would be found to

have the same planes of symmetry as the crystal itself. Lines drawn in the same way in one plane, drawn, say, upon a crystal face, would give an "elasticity curve" characteristic of that face.

Comparative experiments have been made upon calcite and dolomite, and the adjoining Figs. 266, 267, represent the elasticity curves belonging to a rhombohedron face of each; the former is symmetrical to the shorter diagonal of the face, and indicates that the crystal has the complete symmetry of the calcite class; but the latter has not this plane of symmetry, and indicates that dolomite belongs to the dioptase class, a fact which had been suspected from goniometrical measurements but was difficult of proof on that ground alone.

Where it has only been necessary to compare the elasticity in different directions without actually *measuring* it in any direction, other devices have been employed.

Thus the note produced by a vibrating rod depends mainly upon the elasticity in the direction of the rod. Bars of the same dimensions

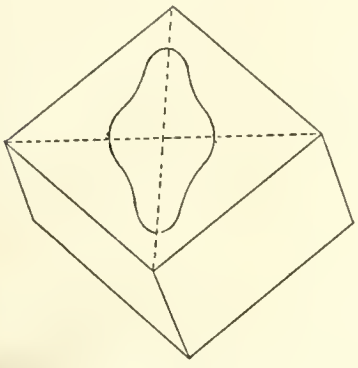


Fig. 266.—Calcite, Elasticity Curve.

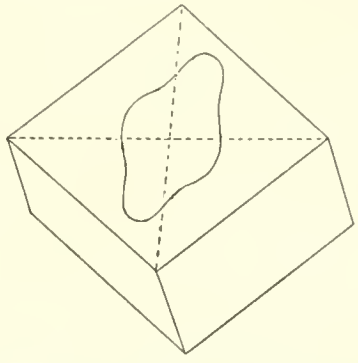


Fig. 267.—Dolomite, Elasticity Curve.

cut out of rock crystal in different directions have been found to give different notes when fixed at one end and set vibrating; but in this, as in all cases, bars cut in directions which are similar in the crystal will give the same note because they have the same elasticity.

2. **Cohesion.**—This property has been sufficiently illustrated above by the cleavage of crystals. If there be a cleavage parallel to one face it always takes place also, and with equal facility, parallel to all the faces of the form to which that face belongs.

This shows that the plane surfaces of minimum cohesion are parallel throughout the crystal, and are repeated over all its planes of symmetry.

Closely allied to the cleavage, and evidently a result of the different cohesion in different directions, are the so-called "percussion figures" (*Schlagfiguren*). If a crystal face be struck with a sharp point, an indentation is made from which certain lines radiate; these are lines of easy separation in the crystal, and may possibly correspond to cleavages; but they are sometimes obtainable when cleavages parallel to them cannot be produced, and they then give a further insight into the symmetry.

If a cleavage face of mica be struck vertically by a sharp blow from a

pointed punch a six-rayed star is produced, whose rays determine three directions in the face.

Crystals of mica are hexagonal in appearance, but one of these percussion rays is far more definite than the other two, and may be easily distinguished from them (Fig. 268).

The hexagonal plates are in reality monoclinic, and are a combination of prism (*m*) and clino-pinakoid (B) terminated by the basal cleavage; their plane of symmetry must therefore be parallel to one pair of edges of the hexagon. The more definite ray of the percussion figure indicates the direction of the plane of symmetry; without this it might be impossible to say to which of the hexagonal edges the plane of symmetry (clino-pinakoid) is parallel.

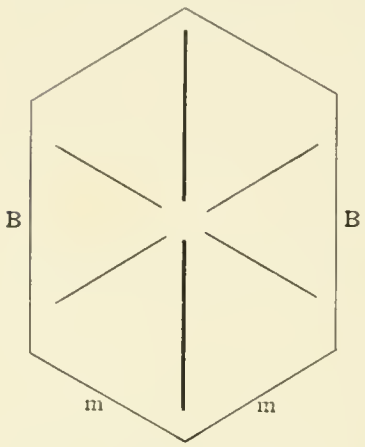


Fig. 268.—Mica, Percussion Figure.

In the case of mica the cracks produced by placing a cleavage plate upon an elastic surface and pressing upon it with a blunt instrument, the so-called "pressure figures" (*Druckfiguren*), are not the same as the percussion figure produced by a blow from a point, but are perpendicular to the edges of the plate of Fig. 268, so forming a second six-rayed star; but this, like the first, is symmetrical to the plane B.

Some of the lines of percussion-figures and pressure-figures doubtless correspond to glide-planes which are not (as was the case with calcite) necessarily also planes of secondary twinning.

3. **Hardness.**—This character, though not capable of absolute measurement, may be compared in different directions upon the same crystal face, or even upon different crystal faces, by means of an instrument termed the *sclerometer*. In the original form of the sclerometer the crystal was fixed upon a small carriage with the experimental face uppermost; upon this rested a lever armed with a diamond point and weighted; the carriage was set in motion by a weight connected with the carriage by a string passing over a pulley, and the load upon the lever was gradually increased until just sufficient to produce a visible scratch.

The crystal (being mounted upon an adjustable turn-table on its carriage) was then turned through a small angle in its own plane and the process repeated for the new direction. In this way the "hardness" was measured for any number of successive directions in the crystal face; the least load necessary to produce a visible scratch being taken as a measure of the hardness in each direction. Now if from any point in a face lines be drawn representing by their length the hardness along those directions, their extremities will trace out the "curve of hardness" characteristic of that face. This is found, like the elasticity curve, to be a symmetrical curve having the same planes of symmetry as the crystal; the curves of hardness for the cube and octahedron faces, respectively, of fluor-spar are shown in the adjoining figure (269). On the cube face,

which is intersected at right angles by four planes of symmetry, the curve has ditetragonal symmetry; whereas on the octahedron face, whose normal is an axis of ditrigonal symmetry, the curve also possesses ditrigonal symmetry.

It is evidently difficult to estimate with precision the exact weight for which the scratch becomes visible.

A more precise method of observation is that of Pfaff, in which the diamond point is weighted with a sufficient constant load, and the crystal is drawn to and fro below it a certain number of times in a given direction. The hardness in that direction is then estimated by the amount of material scratched off the face during the process, and this is measured by the loss of weight experienced by the crystal, which is weighed before and after each such operation.

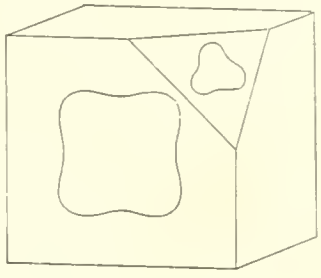


Fig. 269.—Fluor-spar, Curves of Hardness.

The loss of weight being taken inversely proportional to the "hardness," lines are drawn from a point as before, indicating by their length the hardness in each direction; and the curve of hardness obtained by uniting all their extremities is found to possess the geometrical symmetry of the crystal face upon which the observations are made. It is somewhat difficult to say exactly what is meant by "hardness." In all the above experiments the quality estimated is rather "susceptibility to scratching." In some experiments made by Auerbach the hardness was determined as the resistance offered by the crystal to a spherical surface pressed against it, weighted up to the point at which the elasticity of the crystal is overcome, *i.e.* until cracks are developed at the contact, or a permanent impression is made.

4. **Etched Figures.**—Another extremely important method of investigating the symmetry of a crystal, and one which (like cleavage and susceptibility to scratching) may be regarded as based upon differences of cohesion in different directions, is the etching or corrosion produced by a solvent.

When a crystal is acted upon by a solvent, whether water, acid, steam, or a gas, which is capable of dissolving it, the first action of the solvent is not only to dissolve away the projecting parts so as to round off the corners and edges, but also (and sometimes even before such action takes place) the faces themselves are attacked; the process of solution does not go on uniformly over the whole of each face, but begins at different points and proceeds more easily in some directions than in others, with the result that the face becomes covered with regular figures of microscopic size etched upon it by the solvent.

These figures are usually shallow depressions; their sides are minute facets slightly inclined to the face upon which the figures are engraved. These little etched faces are in fact vicinal faces; they belong generally to forms different from those to which the crystal faces belong, and for the most part to forms which are not perpendicular to planes and

axes of symmetry, as is so often the case with the natural faces of a crystal.

For this reason these etched figures are of the greatest possible value in indicating the true symmetry of a mineral.

For example, a cleavage rhombohedron of calcite immersed in dilute hydrochloric acid becomes covered with the little pit-marks shown in Fig. 270. These are strictly in accordance with the supposition that the crystal possesses at least three planes of symmetry; for each little etched figure possesses one line of symmetry parallel to the shorter diagonal of the rhombohedron face, so indicating that a plane of symmetry intersects that face perpendicularly.

On a cleavage rhombohedron of dolomite, on the other hand, the etched figures are asymmetric in outline (Fig. 271), indicating that there is not a plane of symmetry perpendicular to the rhombohedron face.

In interpreting the etched figures on any crystal it must be borne in mind, not only that the shape of the figure etched upon each face indicates

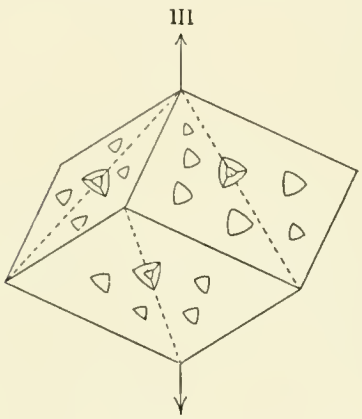


Fig. 270.—Calcite etched with HCl.

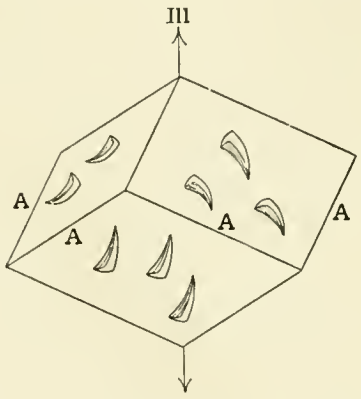


Fig. 271.—Dolomite etched with HCl.

the symmetry of that face, but also that all those faces upon which the same figure is etched must belong to the same form.

Now the figures upon the three upper rhombohedron faces of Fig. 271 are similar, and are enantiomorphous with those upon the three lower faces. The crystal, therefore, possesses one alternating axis of hexagonal symmetry. Hence while calcite is dihexagonal, dolomite is hexagonal and belongs to the dioptase class; this conclusion is fully confirmed by other rhombohedron faces (like *s* in Fig. 187), which occasionally, though rarely, appear upon natural crystals of dolomite. The ordinary combinations do not enable the mineral to be distinguished from one which has the dihexagonal symmetry of calcite. Reference to Figs. 266 and 267 shows that the evidence of the etched figures is precisely the same as that of the elasticity figures.

The value of experiments on etching is well illustrated by the case of two minerals which crystallise in hexagonal prisms. A hexagonal prism terminated by the basal pinakoid may belong to almost any class of the hexagonal system. Such a prism of calcite etched with hydrochloric acid gives the figures shown in Fig. 272. The equilateral triangles upon the

basal plane show that this face is perpendicular to an axis of at least trigonal symmetry. The similar curved figures upon each of the prism faces show quite clearly—

(1) That the six prism faces belong to the same form;

(2) That each is perpendicular to a vertical plane of symmetry;

(3) That axes of digonal symmetry emerge through the prism edges, but not perpendicularly to the prism faces.

The crystal must therefore belong to the class possessing three planes of symmetry intersecting in an axis of alternating dihexagonal symmetry, and is the prism of the first order $\{2\bar{1}\bar{1}\}$. The figures upon adjacent prism faces being inverted with regard to each other, each face must be derived from its neighbour by repetition about a hexagonal axis of symmetry combined with reflection over a plane.

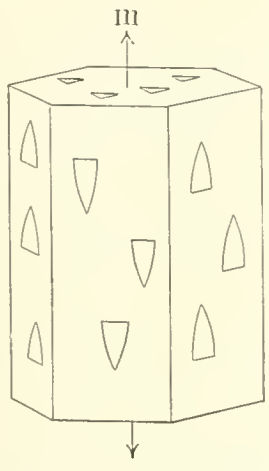


Fig. 272.—Calcite etched with HCl.

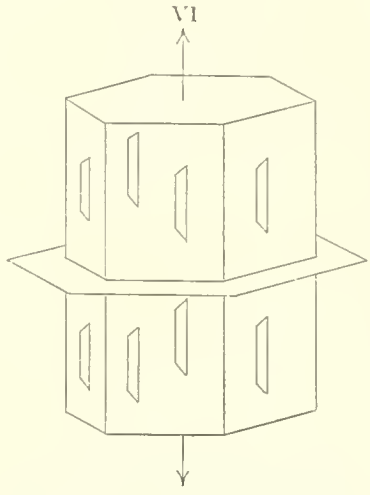


Fig. 273.—Apatite etched with HCl.

A similar prism of apatite etched with hydrochloric acid shows the figures of Fig. 273. Here the figures on each prism face are similar and not inverted—they can only be obtained from each other by repetition about a vertical axis of hexagonal symmetry. Further, the figures, unlike those of calcite, are similar at their upper and lower ends; hence the crystal also possesses an equatorial plane of symmetry perpendicular to the hexagonal axis, as shown in the figure.

It is customary to distinguish the faces which are produced by corrosion upon the corners and edges of a crystal as "prerosion faces," while the term etched faces is reserved for those minute planes which form the sides of the etched figures.

A closer study of the etched figures upon various minerals shows that they are of two sorts; some faces of the crystal become covered with minute depressions or pits, others with minute elevations or hillocks; the latter are really due to the production of such large and numerous pits that the face is nearly completely etched away, and the intervening spaces constitute the hillocks. Those crystal faces, therefore, which are etched into hillocks are precisely the faces which oppose least resistance to the solvent and are most rapidly etched away.

The whole process may be described as the production of planes which lie near to but are not coincident with certain simple forms, and occupy variable positions in certain simple zones; in other words, they are vicinal planes.

Thus magnetite etched with acids gives triangular pits upon the octahedron faces, rectangular pits upon the dodecahedron, and square hillocks upon the cube (Fig. 274). All these figures are bounded by minute facets in the zones of the octahedron edges, for the most part three-faced octahedra; these are sometimes the same on the various crystal faces, and reflect light from a distant flame simultaneously in the same direction, giving the crystal a drusy aspect. The corrosion then of magnetite simply consists in the production of etched faces, which are mainly those of three-faced octahedra, and would therefore replace the edges between octahedron and dodecahedron; the pits upon the octahedron and dodecahedron faces and the pyramids upon the cube faces are bounded by the facets of such forms.

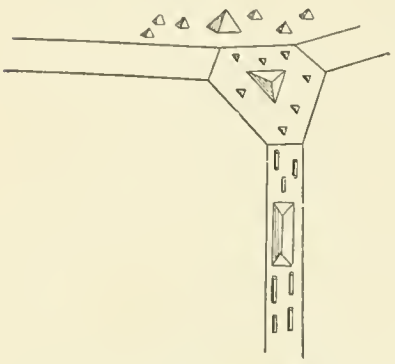


Fig. 274.—The Etching of Magnetite.

The etched faces appear to be planes having indices which are rational, although not in general simple. The probability that they do obey the law of rational indices is suggested by the fact that they always lie in certain well-defined zones of the crystal; in this respect they resemble the vicinal faces described on p. 96.

There is yet another method of investigating the action of solvents. A crystal is cut into the form of a sphere and immersed in the solvent; after being subjected to the action for some time the sphere will have altered in shape, and the comparative extent to which corrosion has taken place in different directions may be ascertained by careful measurement of the different diameters; or again, a cylinder is used whose axis is parallel to that of a given zone in the crystal, so that the comparative rates of corrosion in directions perpendicular to the various faces of the zone may be measured by the decrease of different diameters of the cylinder.

In this way it has been proved that those directions along which the greatest corrosion has taken place are nearly perpendicular to the faces upon which etched hillocks are produced, and that those directions along which the least corrosion has taken place are nearly perpendicular to the faces upon which pits are etched; further, that during the corrosion of a sphere certain more or less plane surfaces are developed which are parallel to crystal faces. These planes are generally somewhat rounded, but they are approximately parallel to the little etched faces which form the sides of the pits and hillocks upon an etched crystal.

Both the form of the etched figures and the indices of the etched faces depend upon the nature and concentration of the solvent. The rhombohedron faces {100} of calcite etched with hydrochloric acid yield figures

shown in Figs. 270 and 275 (*a*); treated with sulphuric acid they are etched as in Fig. 275 (*b*).

Experiments with hydrochloric acid on cylinders of calcite indicate that with a more concentrated solvent the etched faces are produced more readily and in greater perfection than with a dilute solvent.

Etched figures are not only produced by artificial means, they often occur in minerals as a result of the corrosion by the natural solvents (such as carbonic acid, or water acting under pressure at a high temperature), which play so important a part in the changes in the earth's crust.

The most beautiful triangular figures are often found upon the natural octahedron faces of diamond, and are supposed to be of this nature (Fig. 276).

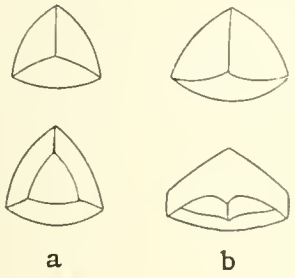


Fig. 275.—Calcite etched with (*a*) Hydrochloric Acid; (*b*) Sulphuric Acid.

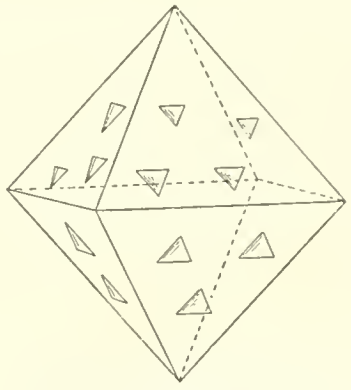


Fig. 276.—Diamond, Natural Etching.

Precisely similar figures are produced on alum by merely passing a moist cloth rapidly over the surface of an octahedron of this substance. They are little pits whose sloping sides are facets belonging to a flat three-faced octahedron like the vicinal faces mentioned on p. 98. Hence an octahedron of alum will always give a triangular light figure (p. 98), whether it be the natural surface or an etched surface, since in either case facets of a flat three-faced octahedron are present.

5. **Pyro-electricity.**—A remarkable property of certain crystals is peculiarly characteristic of those which possess polar axes of symmetry, and it may most readily be observed in tourmaline.

If a crystal of tourmaline be heated, it is found that while the temperature is rising, one end (namely the lower end of Fig. 184) becomes negatively, and the other end positively electrified.

Tourmaline not being a conductor, these electrifications appear as statical charges upon the two ends. While the crystal is cooling their nature is reversed, the positive charge appears at the lower end, and the negative at the upper end of Fig. 184. An ingenious method of observing these differences was devised by Kundt: a mixture of finely powdered red lead and sulphur is dusted or blown through a tube or through a small sieve of fine muslin upon the crystal; during their passage through the sieve the particles become electrified by mutual friction, the sulphur negatively and the red lead positively; the former is then attracted

towards those parts of the crystal which are charged with positive, and the red lead to those which are charged with negative electricity. Thus in the tourmaline crystal of Fig. 184, while the temperature is falling the lower end becomes covered with the yellow sulphur, and the upper end with the red powder, so that the two regions are made clear to the eye.

Such a crystal is said to exhibit pyro-electricity. The two ends are distinguished as "analogous" and "antilogous"; the analogous end is that at which the nature of the charge is analogous to the change of temperature, addition of heat producing a positive, and diminution of heat a negative charge. Thus the upper end of Fig. 184 is that at which cooling produces a negative charge, and is therefore the analogous pole. It will generally be found that the more acute end of a tourmaline crystal is the antilogous, and the more obtuse end the analogous pole.

The same property of pyro-electricity is possessed in a marked degree by the zinc silicate, hemimorphite, of Fig. 231, which is indeed often known by the name of "Electric Calamine." Here, also, the more acute end of the crystal is the antilogous pole.

Both these minerals are polar, that is to say, as explained above (p. 44), they possess a principal axis of symmetry which is geometrically dissimilar at its two ends—it has a certain polar character. Consequently in this direction the physical property of electrification is also of a polar nature. Now such crystals are only a particular case of the more general class comprising all crystals which are devoid of centro-symmetry; in any such crystal there are certain directions which are polar in character, although there may be other directions which are not polar; certain lines will be directions along which the crystal exhibits pyro-electricity if it be a non-conductor; along those directions which are not polar the crystal will not exhibit a pyro-electric character. In such crystals, therefore, if they be dusted with the mixed powders during a rise or fall of temperature, certain parts will become covered with the red lead, and the opposite parts with sulphur; and Kundt's method enables us to explore the whole surface of the crystal at the same time.

A simple quartz crystal becomes positively electrified (yellow) on three alternate prism and pyramid edges, and negatively (red) on the remaining edges.

This indicates that the horizontal axes of symmetry in a quartz crystal are polar; on the other hand, the vertical axis of trigonal symmetry is not dissimilar at its two ends; the upper and lower vertices of the crystal are similar, and the crystal does not exhibit pyro-electricity in this direction. It will be evident, on reflection, that the existence of the horizontal symmetry axes prevents any polarity in the vertical axis, since by rotation about them the two ends of the latter are interchangeable.

Again a crystal of boracite (Fig. 80) will become red on four of its corners, corresponding to one tetrahedron, and yellow on the remaining four corners, which correspond to the supplementary tetrahedron.

All the above observations lead to the same general result, that the physical properties of a crystal obey the laws of geometrical symmetry, in the sense that all the parts of a crystal which are geometrically identical are also invested with the same physical characters as regards elasticity, cohesion, solubility, or electrification. Hence it will be readily understood that it is always advisable, if not necessary, to confirm the results of goniometrical measurement by the application of one or more of the tests above described. Of these the etching and pyro-electric properties are extremely easy of application, and should never be neglected.

There are certain other physical properties which are also of the greatest possible value in indicating the symmetry of a crystal, although they do not serve to distinguish between the presence and absence of centro-symmetry. The conductivity for heat, for example, is in general different in different directions in a crystal but appears to be the same in opposite directions. Such properties may suffice to determine the *System* to which a crystal belongs, although they may not define its exact position among the thirty-two types.

First and foremost of such properties must be ranked the optical characters, which we may now proceed to consider.

CHAPTER VI

ON THE OPTICAL PROPERTIES OF CRYSTALS

1. **Waves of Light.**—When light passes from one point A to another point B in a uniform medium, it may be regarded as a disturbance which travels along the straight line AB, like the wave which may be sent along a rope by shaking one end; and the line AB is called a ray of light.

Before a wave is started the particles of which the rope consists lie at rest on the straight line AB, but at any moment after the disturbance has spread along the line the same particles lie on a wave line as in Fig. 277; each particle has travelled to a certain distance right or left of its original position.

When in the vibrating rope the displacement attains its maximum at the point P, the particle which was originally at O has travelled to P with continually diminishing velocity, and then being drawn back by its neighbours it comes to rest and immediately begins to return with continually increasing velocity towards O. The velocity which it acquires carries it through O to an equally distant point R on the opposite side of the line AB. At this moment the particles originally on the line AB lie on the wave line of Fig. 278. The particle then returns to P and the oscillation is repeated; similar oscillations are made by every particle, and in this way is produced a series of waves which chase one another along the line AB, although each particle only vibrates backwards and forwards at right angles to AB. Whatever may be the change of state to which light is really due, the principles of wave motion afford a very satisfactory geometrical description of optical phenomena.

The intensity of any light may be supposed to depend upon the extent of the vibrations, that is upon the distance 2OP or the "amplitude"; the intensity being proportional to the square of the amplitude. The colour of the light may be supposed to depend upon the distance between successive troughs or successive crests of the wave line; this distance is called the "wave-length," and is denoted by λ. The position of any particle and the direction in which it is moving at any moment define the "phase" of the wave at that point.

At any two points, such as A and S, which are separated by the

interval λ, the phase is the same. The waves of Figs. 277 and 278 are said to differ in phase by half a wave-length or $\frac{\lambda}{2}$, because one is precisely what the other would be if shifted along AB through a distance $=\frac{\lambda}{2}$, so that A would occupy the position A_1.

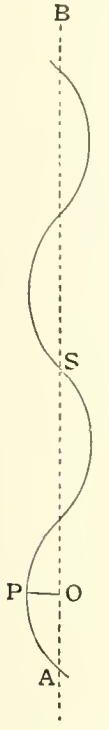


Fig. 277.

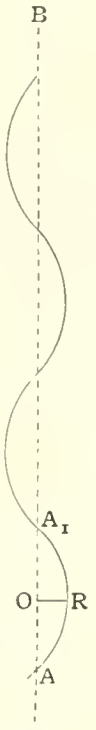


Fig. 278.

Figs. 277, 278.— Difference of Phase.

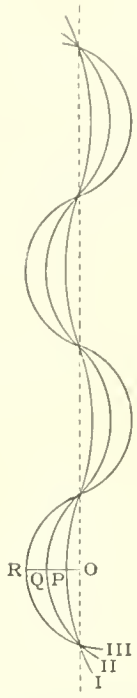


Fig. 279.—Resultant of Two Waves.

2. **Interference.**—When two waves of the same wave-length and in the same phase, but of different intensities, are travelling along the same line at the same time, a particle at O will be affected simultaneously by both wave-motions (Fig. 279); if then P be the point to which it would oscillate by virtue of one wave, and Q the point to which it would oscillate at the same moment by virtue of the other, it will actually move to R where $OR = OP + OQ$. Hence the joint effect of the two waves (I, II) will be to produce one wave (III) of the same phase and wave-length but of greater intensity. The phase remains the same, for the troughs and crests of the constituent waves coincide, so that the troughs and crests of the resultant wave must also coincide with them.

Such a combination of waves to form new waves is called "*interference.*"

When the two waves which interfere differ also in phase, not only the amplitude but also the phase of the resulting wave will be altered.

Now when the two waves are equal in amplitude and wave-length, but differ in phase by $\frac{\lambda}{2}$ as in Figs. 277 and 278, it follows that a

particle such as O will be urged at the same moment to precisely the same extent in opposite directions, to P and to R, and must therefore remain at rest. This is true for every point on the line AB; the two waves will then destroy each other, and, if the analogy be complete, two waves of light related to each other in this manner may by their mutual action produce darkness. Hence if by any means two precisely similar trains of waves identical in wave-length, amplitude, and all other respects, can be made to differ in phase by half a wave-length, and to travel along the same line, they will completely destroy each other.

Complete identity of the two trains of waves is secured by deriving them simultaneously from the same source of light.

To be of the same wave-length they must be of one and the same colour. Now ordinary white light is composed of lights of various wave-lengths; but a monochromatic light (or light of single wave-length) may be obtained by volatilising certain metallic compounds. A nearly uniform or monochromatic yellow light (a "sodium flame") is produced by heating any salt of sodium in the flame of a spirit lamp or Bunsen burner. Thallium salts may be used to produce a green, lithium salts to produce a red flame.

The corresponding wave lengths are:

Lithium	$\lambda = 0{\cdot}000671$ mm.
Sodium	$0{\cdot}000589$ mm.
Thallium	$0{\cdot}000535$ mm.

Two identical trains of waves having been derived from such a monochromatic source of light, any method by which one is made to travel for a time with less velocity than the other, or to traverse a longer path, so that when they are combined they differ in phase by $\frac{\lambda}{2}$, may be utilised to produce their total interference. A mutual extinction of the two will evidently result when they differ in phase not only by $\frac{\lambda}{2}$ but by $\frac{3\lambda}{2}$, $\frac{5\lambda}{2}$, or by any uneven multiple of half their wave-length.

We shall now consider two methods by which this result is produced, one without the action of a crystal, the other leading to very similar effects, but due entirely to the action of a crystal. The former is of importance as an explanation of the colour and superficial appearance of many minerals; the latter of far greater importance as one of the most characteristic physical properties by which a mineral may be identified.

3. **Colours of Thin Plates.**—Among the most familiar effects of interference are the colours of thin films, such as the iridescence of tempered steel, which is due to a thin layer of oxide, or the brilliant tints of a soap-bubble, or the coloured bands visible in glass or other transparent substances when they are traversed by fine cracks.

All such effects are known as the "colours of thin plates."

We shall consider first a thin film surrounded by air, such as the soap-bubble (Fig. 280).

Let AB, CD be the parallel surfaces of the film; consider a ray of light OP incident at P; this is partly reflected at the surface, and partly refracted into the film; let NPN_1 be the normal to the surface at P. Then the reflected ray takes the course PQ, such that the angle of reflection QPN is equal to the angle of incidence $= OPN = i$; the refracted ray takes the course PR_1, where $N_1PR_1 = r$, the angle of refraction: let V be the velocity in air of the incident light, v its velocity within the film, then $\frac{\sin i}{\sin r} = \frac{V}{v} = \mu$, the index of refraction of the film. If the film consists of water surrounded by air, then μ is about 1·3.

The refracted ray on meeting the second surface of the film at R_1 is again partly reflected and partly refracted; the reflected portion R_1S_1 has an angle of incidence, and therefore also of reflection, equal to r; conse-

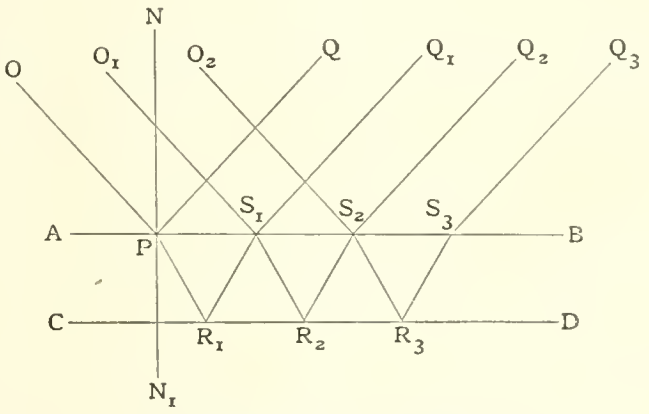


Fig. 280.—Action of a Thin Plate.

quently it meets the first surface again at S_1 with an angle of incidence r. Here again the ray is partly reflected and partly refracted.

The angle of emergence of the refracted ray S_1Q_1 is found as usual by the construction

$$\frac{\text{sine of incidence at } S_1}{\text{sine of refraction at } S_1} = \frac{\sin r}{\text{sine of refraction}} = \frac{r}{V} = \frac{\sin r}{\sin i} \text{ from above.}$$

Hence i is the angle of emergence at S_1, and the ray S_1Q_1 is parallel to the original reflected ray PQ.

The ray reflected back into the film at S_1 behaves in all respects like the ray PR_1, to which it is parallel; it is reflected at R_2, meets the first surface again at S_2, and is there reflected along S_2R_3, and refracted out along S_2Q_2 parallel to S_1Q_1. Inside the film the course of the ray is always inclined at the angle r to the normal, and outside the film at the angle i.

Hence the incident ray OP gives rise to a series of rays which emerge in parallel directions at $S_1S_2S_3$, etc., after undergoing respectively 1, 3, 5, etc., internal reflections at the surfaces of the plate.

Now the incident light being necessarily not a single ray, but a beam of parallel rays, any point such as S_2 is a point from which emerges not only a ray $O_1S_1R_2S_2Q_2$, which has suffered one reflection within the film, but also a ray $O_2S_2Q_2$, which has been directly reflected at S_2. Of these two rays the first has travelled a certain distance along O_1S_1 in air, and the distance $2S_1R_2$ in water, while the second has travelled only along O_2S_2 in air before they meet at S_2. When the former ray catches up the latter at S_2 they unite as coincident rays of light, resembling each other in all respects save that they have traversed different distances in air and water, and that the former has experienced one *internal* reflection while the latter has experienced one *external* reflection, and they will consequently differ in phase.

Let the light employed be monochromatic light of wave-length λ; the distance $2R_1S_1$ depends only upon the angle of incidence of the light, upon the thickness of the film, and upon its refractive index. If then films of different thickness be successively employed without changing the angle of incidence, it will be possible to find one thickness for which the difference of phase is exactly equal to $\frac{\lambda}{2}$. In this case the rays will so interfere as to produce complete darkness. For a greater thickness the total difference of phase may be $\frac{3\lambda}{2}$, and there will again be complete interference. This will also be the case for successive thicknesses, which correspond to a total difference of phase $\frac{5\lambda}{2}$, $\frac{7\lambda}{2}$, etc.; with films of intermediate thickness there will be only partial interference, and consequently the light will not be completely extinguished.

These changes can be observed, occurring in the reverse order, in a soap-bubble, which is gradually becoming thinner just before it breaks. A more convenient method is to use a permanent film of gradually varying thickness, *i.e.* one which is slightly wedge-shaped. The experiment can be made by pressing a glass plate (microscope slide) upon a rather flat glass lens or watch-glass (Fig. 281), illuminating it by the monochromatic yellow light of a sodium flame (S), and viewing it by the obliquely reflected light; the film of air between the plate and the watch-glass now varies in thickness regularly and equally in all directions from the point of contact, and has a constant thickness on any circle of which this point is the centre.

A series of black and yellow circular rings will now be observed (Fig. 282), whose centre is occupied by a black spot corresponding to a film of almost no thickness. The black spot is due to the interference of the superficially reflected light with that immediately reflected from the lower surface of the film at this point. An internal reflection, in fact, produces a difference of phase $\frac{\lambda}{2}$ as compared with an external reflection, and this is to be added to the difference of phase due to the excess of

the path in the film over that in the external medium. The first black ring is that due to the extinction of the light which has traversed a thickness of film just sufficient to produce the difference of phase λ, which, together with that due to one internal reflection, amounts to $\frac{3\lambda}{2}$; the second is due to a total difference of phase $\frac{5\lambda}{2}$; the third $\frac{7\lambda}{2}$, etc.; for each of which retardations the light is extinguished.

Next suppose ordinary white light and not monochromatic light to be used; again a series of circular rings surrounding the point of contact will be seen, but the rings are now brilliantly coloured, like the bands of colour seen by daylight in the soap-bubble film first considered. The rings produced in this experiment are known as Newton's rings; the

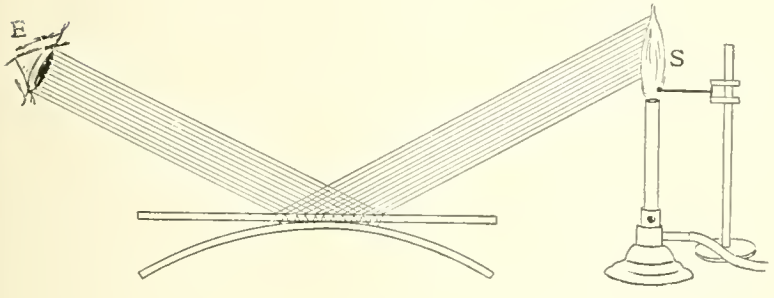


Fig. 281.

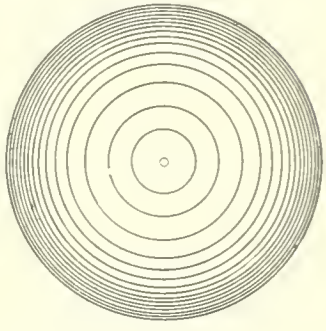


Fig. 282.

Figs. 281, 282.—Newton's Rings.

succession of colour, which was first studied by Newton, must receive our closer consideration.

4. **Newton's Scale of Colours.**—White light is a mixture of lights of various colours or wave-lengths. These travel with different velocities and are differently refracted; so that white light may be separated by refraction through a prism into the various colours of the spectrum, ranging from the violet light of smallest wave-length and greatest refrangibility, through blue, green, yellow and orange to the red light of greatest wave-length and least refrangibility. When the interference rings are observed by monochromatic blue light of small wave-length, the successive thicknesses of film, which correspond to differences of phase of $\frac{\lambda}{2}$, $\frac{3\lambda}{2}$, etc., are smaller than those for yellow light, and these again are smaller than those for red light; hence the rings as seen with blue light will not be so broad as those seen with yellow light, and the latter are not so broad as those seen with red light.

Newton's rings, as seen by ordinary daylight, are simply the result of superposing all the effects due to light of different colours, the closely-packed rings of blue light upon the wider rings of yellow and still wider rings of red light, and the resultant effect is a series of coloured rings which succeed each other in a recurring order.

Immediately round the point of contact the rings make their appearance. As the slip is pressed against the watch-glass each band of colour

broadens and travels outwards from the point of contact, and is succeeded by others; the colours following each other in the order of decreasing wave-length. Near the centre the stratum of air is so thin that the first colours are due to differences of phase within the film equal to only one wave-length of various lights. The succeeding colours are due to differences of phase equal to two wave-lengths, etc. The colours of the first band are called the colours of the first order; those of the second band the colours of the second order, and so on, the transition from each order to the next higher being made in passing from red to blue. The colours of the first order are partly faint and weak; those of the second order are the most vivid; the succeeding orders become more confused and less vivid, until after the fifth or sixth order the overlapping of the narrow rings produces so mixed an effect that the colours are entirely lost, and white light, so-called "white of higher orders," is produced. These coloured rings are to be compared with those produced by a uniaxial crystal in a polarising microscope, described on p. 146, which they closely resemble.

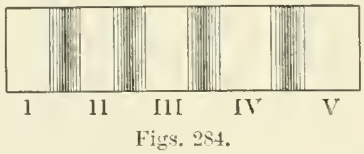
An experienced eye can easily distinguish between the various colours of the first three orders. The succession is as follows:—

First Order.	*Second Order.*	*Third Order.*
Faint gray.	Violet.	Light blue.
White.	Deep blue.	Bright green.
Straw-yellow.	Light green.	Yellowish-green.
Deep red.	Light yellow.	Faint red.
	Bright red.	

The most conspicuous colours are the white, dark yellow, and dark red of the first; the blue, bright yellow, and bright red of the second; and the green of the third order. The most brilliant region of colour is that comprised between the yellow of the first and the blue of the second order.

If a simple wedge-shaped film be used, *e.g.* the film of air between two glass plates AB, CD (Fig. 283), which have been cemented together, and have become slightly separated at the end BD, the colours are no

Fig. 283.



Figs. 284.

Figs. 283, 284.—Interference produced by a Thin Wedge.

longer circles but straight bands, as in Fig. 284. The colours and the sequence of the various orders being, however, precisely the same as before. This series of bands is to be compared with those given by a quartz wedge in the polarising microscope as described on p. 172.

A series of colours similar to those of Newton's rings will result from any contrivance which causes the interference of white light by continually increasing differences of phase; for this leads to the successive

extinction of all lights of different wave-lengths in the same sequence. A very important case will be shortly considered in the interference phenomena of crystals produced through the agency of "polarised light."

5. **Plane-Polarised Light.**—A rope suspended by one end may have a wave tremor sent along it in various ways; the free end may be shaken with a simple backward and forward movement along one line, waves will then be produced in which all the oscillations take place in one plane; or the free end may be shaken with a circular or irregular movement, waves which may possess the same wave-length and amplitude as before will then travel along the rope, only with this difference that each particle no longer oscillates along one line, but describes a circle, ellipse, or other curve about its original position.

Ordinary light may be regarded as sets of waves of the latter sort, but by appropriate means it is easy to obtain a particular sort of light, which may be regarded as due to oscillations in one plane. This is known as *plane-polarised light*, and is distinguished from ordinary light by the following among other properties.

Let a slice of tourmaline, cut parallel to the principal axis of the crystal of Fig. 184, be placed in its path, so that the light is incident upon it perpendicularly; then as the slice of crystal is rotated in its own plane, it will be found that the light is only completely transmitted when the axis lies in one particular direction; and that when the plate is turned through 90° from this position the light is completely absorbed by the crystal. Ordinary light, on the contrary, is transmitted equally whatever position the axis of the tourmaline may occupy as the plate is rotated in its own plane.

Plane-polarised light may be produced in various ways. When light, O,

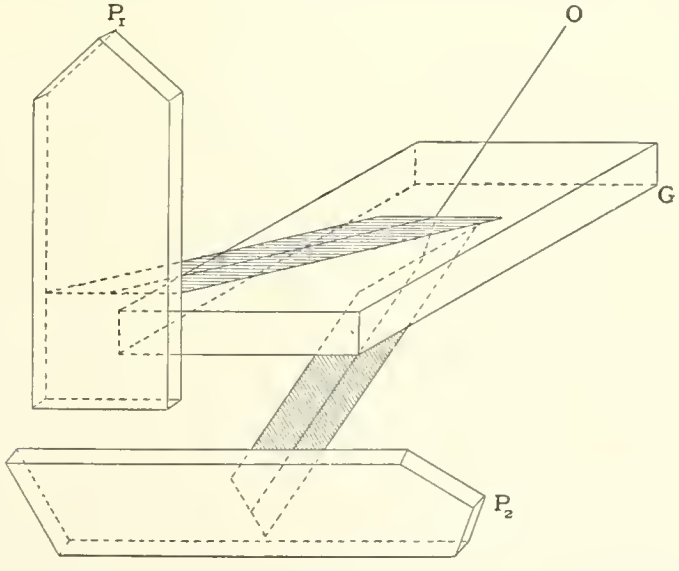


Fig. 285.—Examination of Polarised Light by a Tourmaline Analyser.

is incident on a surface, G, of ordinary glass at an angle of about 56° (Fig. 285), the reflected beam is plane-polarised; if examined by means of the plate of tourmaline it is found to be completely absorbed when the

axis of the tourmaline lies in the plane of incidence, as in P_1 of Fig. 285, and to be completely transmitted when the axis of the crystal is perpendicular thereto.

The light refracted through the glass is also plane-polarised, but its properties are different from those of the reflected ray; for it is completely absorbed by the tourmaline when the axis of the crystal is *perpendicular* to the plane of incidence, as in P_2 of Fig. 285.

The reflected light is said to be polarised in the plane of incidence, and the refracted light is therefore said to be polarised in a plane perpendicular to that of incidence.

Another way of obtaining plane-polarised light is to transmit ordinary light O through such a plate of tourmaline cut parallel to the axis of the crystal (Fig. 286). The transmitted light T is found to possess the properties of light reflected from glass so placed that the plane of incidence is perpendicular to the axis of the tourmaline. It is therefore said to be polarised in this plane.

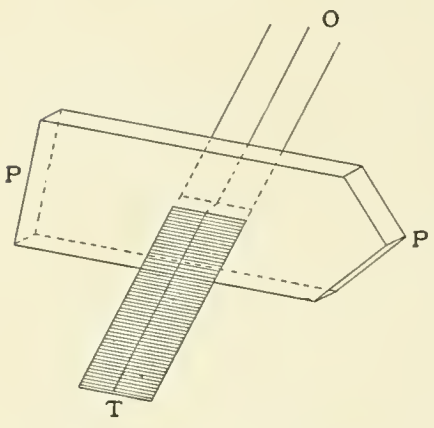


Fig. 286.—Polarisation by Tourmaline.

If the properties of light be compared with those of a vibrating medium, the vibrations of plane-polarised light may be regarded as probably taking place at right angles to the plane of polarisation.

In light reflected from glass they are therefore perpendicular to the plane of incidence; in the refracted light they are in the plane of incidence; in light which has been transmitted through a plate of tourmaline they are parallel to the principal axis.

These directions are indicated by the cross shading in Figs. 285, 286.

Bearing in mind that the conception of light as due to the vibrations of particles at right angles to the path of the light may be no more than a geometrical representation of some recurrent change of state which is not really a vibration, we may continue to speak of a ray of light as due to such vibrations, and of a plane-polarised beam as due to vibrations perpendicular to the plane of polarisation; and of a tourmaline plate as only transmitting vibrations which take place parallel to its axis (as in Fig. 286).

6. **Resolution and Analysis of Polarised Light.**—When light is transmitted through a crystal of tourmaline PP (Fig. 286) it emerges plane-polarised, the vibrations taking place parallel to PP. If another tourmaline crystal be placed above this, with its axis AA perpendicular to the axis PP of the first tourmaline (Fig 287), no light emerging from the first crystal can penetrate the second, for the latter only transmits light vibrating parallel to AA; where the two crystals overlap there will be darkness. If, however, the lower crystal be turned round until it is parallel to the upper one, then the polarised light which emerges from the former will pass unchanged in character through the latter. Let the lower

crystal be now placed in some intermediate position as P′P′ (Fig. 288). A vibration which would transfer a particle of a vibrating medium from O to R may be supposed due to the simultaneous action of two vibrations, one of which would transfer it to M, and the other to N. The vibration OR may be *resolved* into two component vibrations along the directions OM and ON of Fig. 288 respectively, just as a force may be resolved into component forces along two directions at right angles to each other, and its effect studied by observing the separate effects of these two components.

Now of the two vibrations into which OR is supposed to be resolved, the component along ON is completely transmitted by the second tourmaline, while the component along OM is completely absorbed. The result is that if a plane-polarised ray, vibrating along P′P′ with semi-amplitude OR, passes into AA, it is transmitted as a polarised ray with semi-amplitude ON. As the lower crystal is rotated from the position

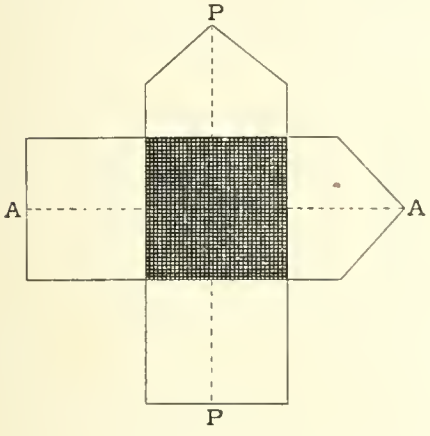


Fig. 287.—Crossed.

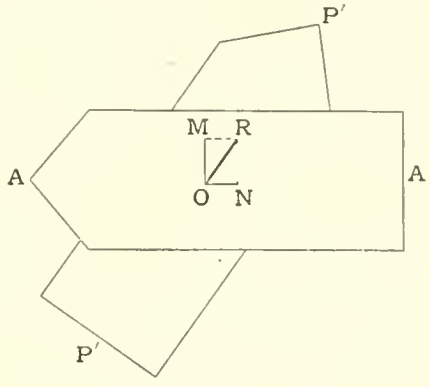


Fig. 288.—Inclined.

Figs. 287, 288.—Polariser and Analyser.

P′P′ to the position PP, more and more of the light is cut off by the upper crystal, until in the latter position it is completely absorbed.

A tourmaline crystal, or other contrivance used like PP to produce a beam of plane-polarised light, is called a *polariser*, that used like AA to examine the same is called the *analyser*.

When their planes of polarisation are at right angles (and therefore also their axes AA, PP,) darkness is produced and the polariser and analyser are said to be "crossed" (Fig. 287).

7. **Action of Crystals on Light.**—When light enters a crystal it experiences certain peculiar modifications which are very remarkable and give rise to the most beautiful effects; these have been minutely studied; they have constituted the basis of the wave theory of light, and they have subsequently proved to be one of the most subtle means of studying the crystalline structure of transparent crystals, and hence also of identifying mineral species.

When a ray of light enters a crystal belonging to the cubic system it is refracted just as it would be on entering a piece of glass or other amorphous substance, and the refracted ray obeys the ordinary law of refraction;

it therefore lies in the plane of incidence, and, if i be the angle of incidence, and r the angle of refraction, then $\frac{\sin i}{\sin r}$ is the index of refraction of the crystal for the particular light employed, and its refractive power is measured by this index. A cubic crystal is therefore said to be "singly refracting" or "optically isotropic."

But when a ray of light enters a crystal belonging to any other system it is in general divided into two refracted rays, neither of which necessarily lies in the plane of incidence. Such crystals are said to be "doubly refracting," or "optically anisotropic," and the angular divergence between the two rays produced is different for different substances and also for different directions in the same crystal.

A crystal whose double refraction is strong may produce so large an angular divergence of the two rays that an object viewed through it will appear double; one image being produced by rays travelling in the one direction and a second by rays travelling in the other. This phenomenon was first observed and studied in the clear transparent variety of calcite known as "doubly refracting spar" or "Iceland spar," which was found in large masses at Eskifjördhr in Iceland.

8. **Double Refraction of Iceland Spar.**—If a cleavage rhombohedron of Iceland spar (Fig. 289) be placed over a black spot on a sheet of

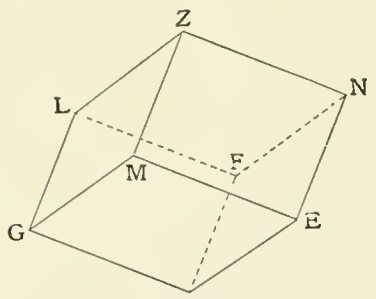


Fig. 289.—Iceland Spar.

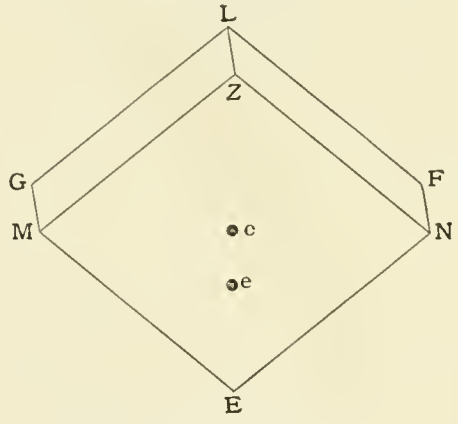


Fig. 290.—Double Refraction.

white paper the spot will appear double (Fig. 290, where the crystal is lying on a face parallel to ZMEN). Of the two images one (o) appears to occupy the position in which it would be seen through a plate of glass or other isotropic substance of the same refractive power; the corresponding ray is therefore refracted according to the ordinary laws of refraction and is called the *ordinary* ray; the other image (e) appears shifted away from the summit Z of the rhombohedron in one of the planes of symmetry of the crystal, *i.e.* along the shorter diagonal ZE of the rhombohedron face. Even when the crystal is viewed perpendicularly to the rhombohedron face the two images are still visible, the ordinary image is seen vertically through the face without any displacement, but the other image is still shifted from the summit; the latter therefore corresponds to a ray which obeys some totally distinct or extraordinary law of refraction, and this is

called the *extraordinary* ray. The course of the rays through the crystal is shown in Fig. 293.

If now these images be examined through the tourmaline analyser it will be found that as the tourmaline is turned round, the ordinary image disappears when the principal axis of the tourmaline is parallel to

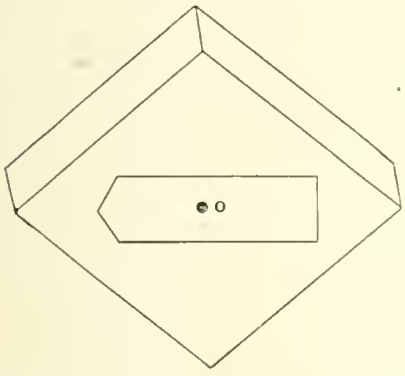


Fig. 291.

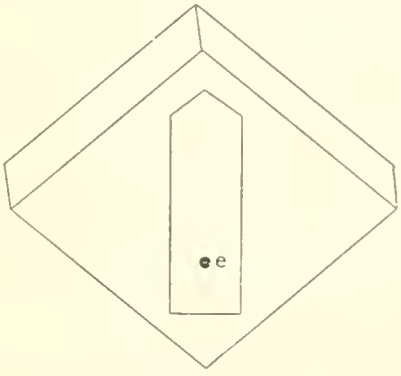


Fig. 292.

Figs. 291, 292.—Analysis of Light transmitted through Iceland Spar.

the shorter diagonal of the rhombohedron face (Fig. 292), and the extraordinary image disappears when the axis is parallel to the longer diagonal (Fig. 291).

This proves that these images are due to two plane-polarised rays, the ordinary polarised in the plane of symmetry, the extraordinary polarised perpendicular thereto.

Hence a ray of light entering a rhombohedron of calcite is separated into two polarised rays—an ordinary ray whose vibrations may be regarded as parallel to the longer diagonal of the rhombohedron face, and an extraordinary ray due to vibrations along the shorter diagonal of the face.

A more satisfactory way of examining a crystal such as calcite, would

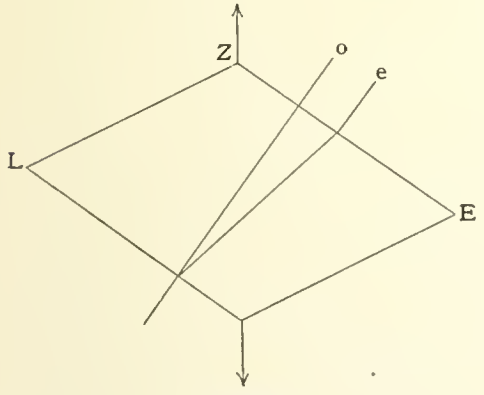


Fig. 293.—Double Refraction in Iceland Spar.

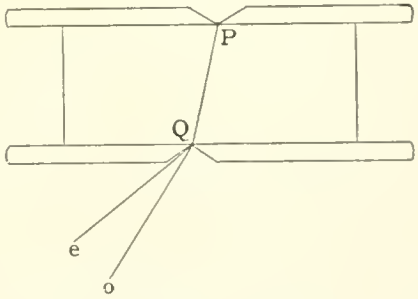


Fig. 294.—Double Refraction.

be to permit the incident light to pass through it *in one direction only* by means of two screens, one having a hole at P and the other a hole at Q (Fig. 294); one screen being placed on one face of the crystal and the other on another face, so that the light can only traverse the crystal in

the direction PQ. By moving the screens the line PQ might be given any required direction. It would then be found that light traversing the crystal in the direction PQ would emerge as two refracted beams, *e* and *o*, polarised at right angles to each other and generally travelling in different directions, so that PQ is a direction along which two rays are transmitted in the crystal—a direction of so-called double refraction.

When crystals of calcite are examined in all possible directions, it is found they are always doubly refracting except along the principal axis. In this one direction, perpendicular to the basal plane, there is no division of the transmitted light into two plane-polarised rays—no double refraction—but in all other directions the transmitted light consists of two polarised rays whose planes of polarisation are at right angles to each other.

9. **Double Refraction of Crystals in General.**—What has been stated above of calcite is equally true of all crystals belonging to the hexagonal system, or to the tetragonal system. Although their double refraction may not be so marked as that of calcite, they will in general transmit light as two plane-polarised rays travelling in the same direction within the crystal, an ordinary and an extraordinary ray; further, they all have one direction along which there is no such double refraction, namely, the morphological or principal axis. A direction along which there is no such double refraction is here called an "*optic axis*"; and minerals belonging to these systems, since they possess only one optic axis, are said to be "*uniaxial.*"

Crystals belonging to the orthorhombic, monoclinic, or anorthic system are also doubly refracting, but light traversing any of these crystals is in general transmitted in any direction as two extraordinary plane-polarised rays, neither of which obeys the ordinary laws of refraction. Crystals belonging to these systems are quite different from uniaxial crystals in that they possess *two* directions possessing most of the features of the optic axis of a uniaxial crystal; they are consequently called *biaxial.*

Crystals may then, in the first place, be divided into the following three important groups :—

Cubic crystals are	. . .	optically isotropic.
Hexagonal and tetragonal	. .	„ uniaxial.
Orthorhombic, monoclinic, and anorthic		„ biaxial.

The property possessed by tourmaline of transmitting at right angles to its axis plane-polarised light, results simply from the fact that of the two rays produced in the crystal, one (the ordinary) is completely absorbed, and only the extraordinary ray is transmitted; its vibrations may be supposed to take place along the axis of the crystal.

10. **Examination of Minerals in Polarised Light.**—The optical characters of minerals are best examined by observing either thin sections cut out of their crystals in known directions, or natural sections obtained by cleavage, or natural plates bounded by a pair of parallel

crystal faces. For this purpose it is necessary to use a microscope fitted with a polariser and an analyser (Fig. 364).

The following are the requirements of a mineralogical microscope: a rotating stage on which the crystal section is placed, a polariser below the stage, and an analyser above the stage, the latter being either in the tube, or above the eye-piece. Both polariser and analyser should be movable, so that they can be inserted or withdrawn at will. The microscope should also be supplied with a lens or system of lenses, which can be inserted immediately below the section so as to concentrate the light after it has passed through the polariser, and bring it to a focus within the crystal if desired.

Since good plates of tourmaline are difficult to procure, and have the slight disadvantage of being coloured, the contrivance known (from the name of its inventor) as a "nicol prism" is generally used for both polarising and analysing the light.

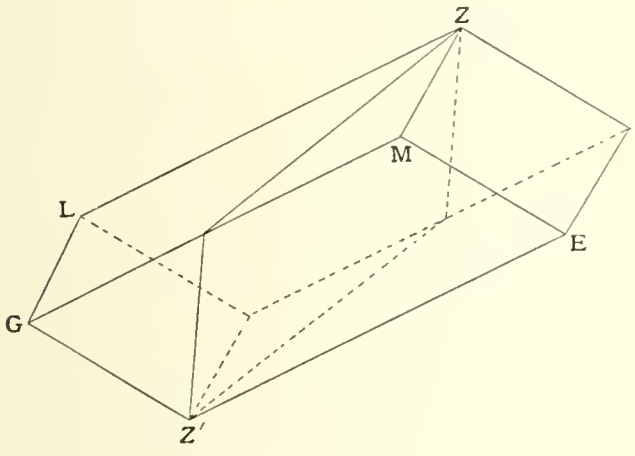


Fig. 295.

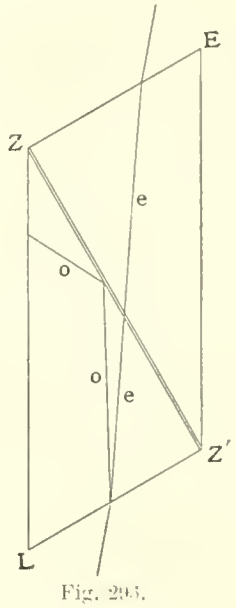


Fig. 296.

Figs. 295, 296.—Nicol Prism.

A nicol prism is made from a cleavage rhombohedron of calcite three times as long as it is broad (Fig. 295; compare Fig. 289): this is cut in half along a plane ZZ′ nearly joining two opposite corners (actually inclined at 22° to the longer edge ZL of the prism); the two halves are then cemented together with Canada balsam. The ends of the prism are planes ground not exactly along the natural cleavage faces, but inclined at 2° 52′ to them so as to be perpendicular to the plane of section ZZ′. The effect of this construction is that when the two rays, resulting from a ray of light which enters the prism at its lower end, reach the film of Canada balsam, one, namely the extraordinary ray, is refracted through it and emerges as a plane-polarised ray vibrating parallel to the shorter diagonal of the prism; but the ordinary ray meets the film at a larger angle of incidence, and one which exceeds 69° 4′, the angle of total reflection for that ray incident on balsam from calcite; this ray is therefore reflected to the side of the prism and is there absorbed by the

surface, which is blackened for the purpose. The prism consequently (like the tourmaline plate) transmits only a single beam of plane-polarised light, the vibrations taking place along the shorter diagonal.

In the ordinary mineralogical microscope a nicol prism is mounted below the stage on an arm by which it can, if necessary, be swung out of the way ; and another nicol is mounted on a sliding piece in the tube. One or each of these is mounted in a ring so that it can be rotated and set with its plane of polarisation at any desired angle to that of the other ; but as a rule the two nicols are kept crossed.

When a low power objective is used and the converging system of lenses or "condenser" is not employed below the stage, all the light which enters the eye-piece has traversed the crystal in one direction, since all the rays have travelled from the mirror to the objective practically along the axis of the microscope ; a crystal observed in this way is said to be examined in "parallel light." When, however, the condenser is inserted below the stage a beam of rays passes into the crystal as a converging cone, whose apex is within the section, and emerges from the crystal as a diverging cone ; a high power objective ($\frac{1}{4}$ inch or higher) must then be used by which these rays are transmitted, through another lens, to the eye-piece. Viewed in this way the crystal is said to be examined in "convergent light."

The following remarkable phenomena are to be observed.

11. **Examination in Parallel Light.**—The nicols being crossed, no light is transmitted through the microscope. When any isotropic substance, such as a plate of glass, is placed on the stage the field remains dark ; any crystal which behaves in this way, or is "inert" in whatever direction it is viewed, is at once known to belong to the cubic system. When, however, a crystal belonging to any other system is placed upon the stage the field in general becomes bright, showing that, on account of the double refraction of the crystal, the plane-polarised light issuing from the polarising nicol becomes partially transmissible through the analyser.

Suppose the crystal to be a very thin section of colourless calcite cut parallel to its principal axis ; viewed by a low power between crossed nicols the section will in general appear brilliantly coloured ; if it be ground thinner and viewed again in the same way the tint will be found to have changed, and will be probably more vivid. Hence the colour depends upon the thickness of the section.

If a number of sections each thinner than the preceding were examined in succession the tints would be found to vary through all the successive colours of Newton's scale from the higher to the lower orders ; in other words, as the crystal section becomes thinner the tints follow the order of those resulting from interference in a thin film as it decreases in thickness.

If now the stage be rotated it will be found that the light transmitted retains the same tint but varies in intensity, and twice during a half rotation it is completely extinguished. This occurs in two positions, which are called the "positions of extinction," and are at right angles to each other ; in the one the axis of the crystal is parallel to the shorter

diagonal of the polariser; in the other it is parallel to the shorter diagonal of the analyser.

Almost all sections of calcite examined in this way exhibit the same characters; the crystal appears bright and coloured between crossed nicols. The colour depends upon the thickness of the section, which becomes quite colourless when sufficiently thick; it depends also upon the direction in which the section is cut; and there are two positions of extinction perpendicular to each other in which the crystal becomes dark as it is rotated in its own plane.

Only when the section is cut perpendicular to the axis are the appearances different; the crystal then remains dark during the complete rotation of the stage. Remembering that calcite is a uniaxial mineral and that this section is perpendicular to the optic axis, so that the light which traverses it in that direction does not experience double refraction, we conclude that in this direction there is no transmission of light through the crossed nicols, because there is no double refraction in the crystal, and that the crystal is dark for the same reason as a cubic crystal.

Passing to biaxial minerals we find precisely similar phenomena, only with the difference that there are now *two* sections which remain nearly dark, like isotropic substances; these are the sections cut perpendicular to each of two optic axes.

In general, therefore, a section of any crystal which does not belong to the cubic system, when examined in parallel light between crossed nicols transmits light of a certain tint depending (1) upon its thickness, and (2) upon the direction in which it is cut out of the crystal; but as the section is rotated in its own plane there are two positions of extinction which are perpendicular to each other. A section cut perpendicular to an optic axis remains nearly dark or is inert when rotated between crossed nicols.

12. **Examination in Convergent Light.**—In the examination by parallel light the effects produced by the passage of light through the crystal, namely, the tint and the extinction, are observed at the same time with the crystal itself, and the objective is so placed that the crystal is in focus.

In the examination with convergent light, it is desired to observe the effects produced upon rays which have travelled in different directions through the crystal, and it is no longer necessary to view the crystal itself at the same time.

The effect to be observed is an interference effect, due to rays which have traversed the crystal in different directions, and is produced at points above the objective where they are brought to a focus, as described below on p. 148.

The different points correspond to rays having different directions in the crystal, and all these points taken together constitute a coloured figure. It will be found, however, that this figure is formed too low in the tube to be viewed by the eye-piece; the effects produced by convergent light are to be observed by removing the eye-piece, when

the coloured figure is seen near the bottom of the tube, just above the objective; or, more conveniently, by inserting a supplementary lens of appropriate focal length at some point between the objective and the eye-piece. Another way of seeing the effects produced in convergent light without removing the eye-piece, in a microscope which is not provided with the necessary lens in the tube, is to hold an ordinary magnifying glass above the eye-piece; the coloured image will then be seen conveniently magnified when the lens is held at the right height above the microscope.

Many sections previously examined in parallel light will now be found to produce systems of the most beautifully coloured and regular bands, known as "interference figures," one form of which is shown in Plate II.

A section perpendicular to the optic axis of a uniaxial crystal gives rise to a black cross intersecting a series of circular coloured rings similar to the series in Newton's rings (Fig. 354); a section perpendicular to an optic axis of a biaxial crystal presents a black bar intersecting a series of slightly oval rings; a section equally inclined to the two optic axes of a biaxial crystal shows two dark bars or "brushes" surrounded by a series of oval or lemniscate rings (Figs. 322-326, and Plate II).

We have now to consider how these interference figures are produced. For this purpose it will be necessary to consider the velocity and condition of the light traversing the crystal.

13. **Rays and Beams of Light in a Crystal.**—The study of refraction has led to the conclusion that within an isotropic medium a luminiferous wave-motion starting from any centre of disturbance O would spread with equal velocity in all directions; hence at all points on the surface of a sphere described about O the phase will be the same. At any such point the *ray*—*i.e.* the direction in which the light has travelled thither from O—is the radius of the sphere; the *front* of the wave is the tangent plane at that point and is perpendicular to the ray.

In a doubly-refracting medium light travels with different velocities in different directions; points at which the phase is the same lie, not upon a sphere, but upon some other central surface whose tangent planes are not in general perpendicular to the radii. Thus in some uniaxial crystals the surface is an ellipsoid like that of Fig. 310, and in order to find the direction of the extraordinary ray by means of the Huygens construction this ellipsoid must be employed in place of a sphere.

Since it is impossible to isolate a single ray, optical experiments are really made with *beams* of light. Consider then a small cylindrical beam travelling in an isotropic medium or a cubic crystal; the points which, at a given moment, are in the same phase, that is to say, the points which in the language of the wave theory are all swinging together in the same direction, lie in the plane of the circle AB which is perpendicular to the beam (Fig. 297). This plane may be called the front of the beam, or the "wave-front."

In a doubly-refracting crystal, on the other hand, the front of the beam is inclined to its direction, and points which, at a given moment, are in the same phase, lie in the plane of the ellipse AB (Fig. 298).

The line perpendicular to the front may be called the *direction of the wave*, as contrasted with the *direction of the ray*.

Refraction through a plate of crystal is represented by Fig. 299. During the course of the two refracted beams through the crystal their fronts are inclined, and unequally inclined to the rays of which they consist. After emergence from the crystal the fronts are again perpendicular to the two beams, one of which has lagged behind the other, so

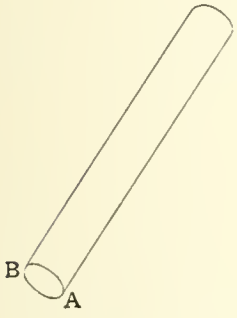


Fig. 297.—Wave-front in Air.

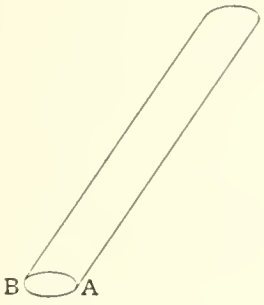


Fig. 298.—Wave-front in Crystal.

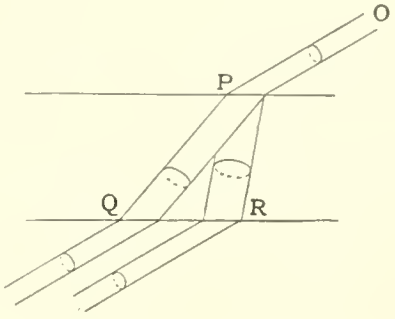


Fig. 299.—Double Refraction.

that they would be in a condition to interfere, were it not that the vibrations of the one are at right angles to those of the other, instead of being parallel with them.

It must be observed that two beams which are inclined to one another within the crystal may have fronts which are parallel, as in Fig. 300; and, similarly, that two beams may consist of parallel rays and yet have fronts which are not parallel, as in Fig. 301.

When the direction of a beam of light, its velocity, the lines along

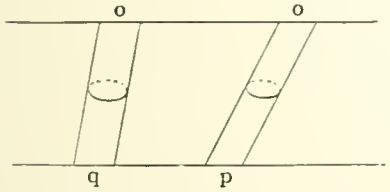


Fig. 300.—Wave-fronts parallel.

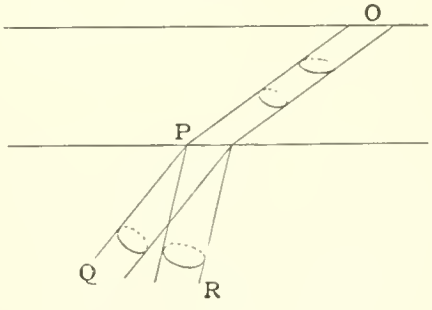


Fig. 301.—Wave-fronts inclined.

which the vibrations of its rays are to be regarded as taking place, and the direction of its front are known, the nature of the beam is defined.

All these properties are in the most general case completely expressed by means of either of two ellipsoids, known as the "Fresnel Ellipsoid" and the "Indicatrix" respectively.

14. **The Fresnel Ellipsoid.**—We have seen that light traversing a crystal in any direction OP (Fig. 301) emerges in general as two beams of plane-polarised light travelling in two different directions PQ, PR. Now refraction at the junction of two media is the result of the difference

between the velocities of light in the two media. Obviously in air the beam PQ travels with the same velocity as PR, hence it follows that within the crystal two polarised beams can travel with different velocities along OP; moreover, these are polarised at right angles to one another; and plane-polarised light is, as we have seen above, to be regarded as due to vibrations executed in a single direction; hence the velocity of the light must vary not only with the direction in which it is travelling, but also with the direction in which its vibrations are executed. In fact it is found that each direction within the crystal is the vibration-line of light travelling in a definite direction perpendicular thereto with a certain definite velocity.

In what follows we confine our attention to light of one and the same wave-length: the light, for example, of a sodium flame.

Let O be a point of reference arbitrarily selected inside a biaxial crystal (Fig. 302). Along any direction can travel in general two rays of light with different velocities. Let, then, the velocities along all possible directions in the crystal be compared with each other with the object of finding: (1) Those along which the light travels with the greatest possible velocity ($=V_a$); (2) those along which it travels with the least possible velocity ($=V_c$). It will be found that there are many directions along which a ray travels with the velocity V_a, but that all these directions lie in one plane. Let this be the plane BOC. Then along any line lying in the plane BOC two rays can be propagated, but the velocity of one of these is constant and equal to V_a, and the ray is polarised in the plane BOC; it would be absorbed by a tourmaline plate whose axis is held in that plane. The velocity of the other ray varies with its direction.

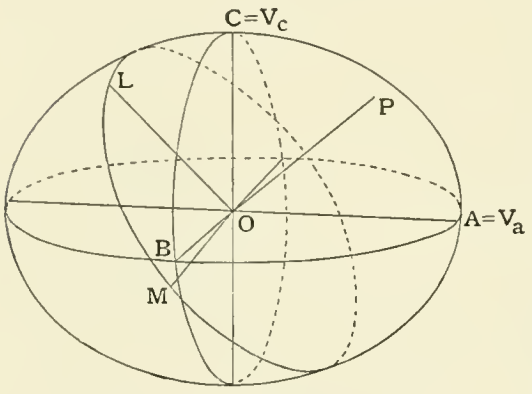


Fig. 302.—The Fresnel Ellipsoid of a (positive) Biaxial Crystal.

Draw OA perpendicular to the plane BOC, and of a length proportional to V_a. This line represents the velocity of all rays whose vibrations take place along OA, according to the convention adopted above, namely, that the vibration-direction is to be regarded as perpendicular to the plane in which the light is polarised.

Similarly, if OC be drawn perpendicular to the plane AOB, which contains all the rays travelling with the minimum velocity V_c, and of a length proportional to V_c, then OC represents the velocity of all rays whose vibrations take place along OC. It will further be found that all the rays travelling in the plane AOC, and polarised in that plane, travel with a constant intermediate velocity V_b. Hence OB drawn perpendicular to the plane AOC, proportional to V_b, represents the velocity of all rays whose vibrations take place along OB.

Thus along OA can travel two rays whose velocities and direction of

vibration are represented by OB and OC; along OB can travel two rays represented by OA and OC; and along OC can travel two rays represented by OA and OB.

Now let an ellipsoid be constructed having OA, OB, OC for its maximum, mean, and minimum semi-axes. This surface, which may be called (from its discoverer) Fresnel's ellipsoid, possesses the following remarkable property.

Take any line OP, and through the centre O draw a plane perpendicular to OP; the plane will of course cut the ellipsoid in an ellipse; this elliptic section will have two principal axes, a major axis OL, and a minor axis OM.

Then it is found that the two plane-polarised rays which can travel through the crystal along OP have both their directions of vibration and their velocities represented by the lines OL and OM respectively.

The faster of the two rays vibrates along OL and travels with a velocity represented by OL; the slower vibrates along OM and travels with a velocity represented by OM. The two rays are further seen from this construction to be polarised in planes perpendicular to each other. It also follows that the two rays which travel along OP, since they are propagated with unequal velocities, have been differently refracted on entering the crystal, and therefore result from two different rays of the incident light which are not parallel; conversely, also, to any one direction of the incident light correspond two different rays inside the crystal; or, in other words, light incident on the crystal is, in general, doubly refracted.

The refractive index for a ray due to vibrations along any one of the three principal axes of the Fresnel ellipsoid being the ratio of its velocity in air to its velocity in the crystal, the refractive index for any such ray, passing from air into the crystal, is inversely proportional to the latter; if, then, α is the refractive index for a ray vibrating along OA, β that for a ray vibrating along OB, and γ that for a ray vibrating along OC, OA is proportional to $\frac{1}{\alpha}$, OB to $\frac{1}{\beta}$, and OC to $\frac{1}{\gamma}$ ($\gamma > \beta > \alpha$). α, β, γ are called the three *principal indices* of refraction; α and β belong to the two rays travelling along OC, β and γ to the two rays travelling along OA, γ and α to the two rays travelling along OB.

The mean index β may be taken as a measure of the refraction of a mineral, $(\gamma - \alpha)$ as a measure of its double refraction.

15. **The Indicatrix.**—Beams of light travelling along any of the three directions OA, OB, OC of Fig. 302 have their fronts perpendicular to the directions in which they are travelling, but this is not the case with beams travelling along other directions, such as OP.

Just as the velocity and direction of vibration of a known ray is found from the Fresnel ellipsoid, so may the velocity and direction of a known wave-front be found from another ellipsoid constructed in the following manner upon the same three lines OA, OB, OC, whose position might be found experimentally as described in the last section.

Take OA (Fig. 303) proportional, not to the velocity, but to that

refractive index which is constant for the beams travelling along different directions in the plane BOC (i.e. *inversely* proportional to their velocity) : OB proportional to that refractive index which is common to beams travelling in the plane AOC ; and OC proportional to the index similarly obtained from beams travelling in the plane AOB ; so that $OA = \alpha$, $OB = \beta$, $OC = \gamma$ $(\alpha < \beta < \gamma)$. Construct an ellipsoid upon these three axes. This ellipsoid has the following property.

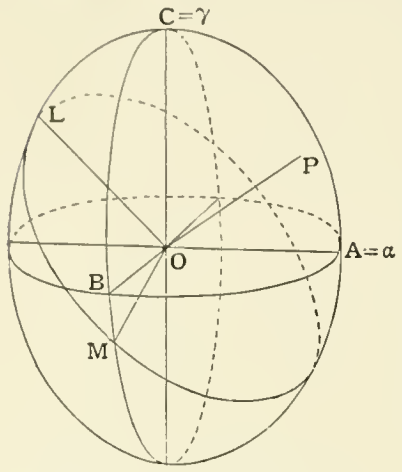


Fig. 303.—The Indicatrix of a (positive) Biaxial Crystal.

Take the elliptic section made by the plane LOM perpendicular to any line OP ; the principal axes OL, OM of this ellipse are proportional to the refractive indices of the two beams of light within the crystal whose wave-directions are parallel to OP, that is to say, whose fronts are parallel to the plane LOM.

Further, these two axes lie in the planes containing OP and the vibration-lines of the two plane-polarised beams. The elliptic section of the indicatrix therefore gives in its axes the refractive indices for the two beams of light and the planes in which they are polarised.

The difference in length of the two axes OL, OM, is a measure of the double refraction or "birefringence" of the crystal in the direction OP, that is to say, of the birefringence of the particular section which is cut perpendicular to OP.

In the Fresnel ellipsoid the axes OA, OB, OC, are in descending order of magnitude ; in the indicatrix they are in ascending order of magnitude ; in the Fresnel ellipsoid they are inversely proportional to the three principal indices of refraction α, β, γ ; in the indicatrix they are directly proportional to the three indices $(\alpha < \beta < \gamma)$.

16. **Biaxial Crystals.**—Any plane section of an ellipsoid is an ellipse, and every ellipse has two principal axes, a major axis and a minor axis ; the section of the indicatrix, for example, by a plane perpendicular to OA, is the ellipse BC, whose major axis is OC, and minor axis OB.

Now consider successive sections made by a plane initially coinciding with AOB as it rotates about OB, until it finally comes into the position BOC (Fig. 304) ; each such section is an elliptic curve, but while one axis of the curve, namely OB, remains constant, the other axis is continually increasing in length from the value OA, which is less than OB, to the value OC, which is greater than OB. Hence some intermediate section, such as P_1BP_1', is an ellipse whose two axes are equal ; in other words, it is a circle.

A line OU_1 drawn from O perpendicular to this circle must lie between OC and OA in the plane COA ; and evidently there must be a similar circular section R_1BR_1' on the other side of the plane COB, whose perpendicular OU_1' lies between OC and OA' ; and $U_1OC = U_1'OC$.

Now the radii of the circular sections are equal ; but they represent

the refractive index for beams whose fronts are perpendicular to OU_1 or OU_1'; hence the beams having these wave-fronts yield the same refractive index and must travel with a single velocity inversely proportional

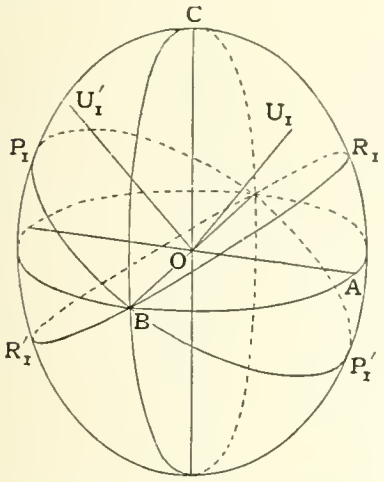


Fig. 304.—The Primary Optic Axes. Circular Sections of the Indicatrix (in a Positive Crystal).

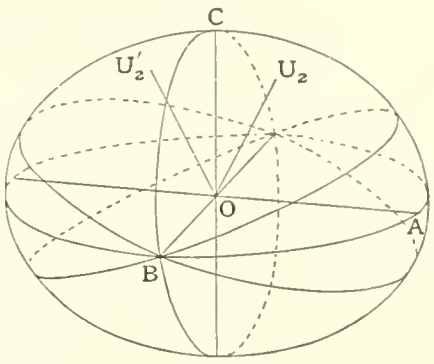


Fig. 305.—The Secondary Optic Axes. Circular Sections of the Fresnel Ellipsoid (in a Positive Crystal).

to OB, and the light traversing the crystal with either of these *fronts* will not be resolved into two definite plane-polarised beams, but may be polarised in any plane.

The two lines perpendicular to the circular sections of the indicatrix

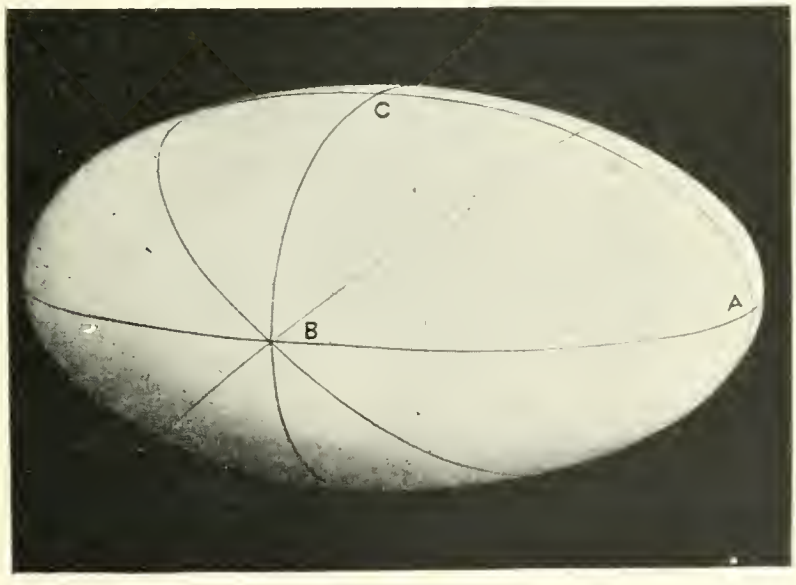


Fig. 306.—Ellipsoid.

Fig. 306 may be regarded as representing either the Fresnel Ellipsoid of a positive crystal or the Indicatrix of a negative crystal, as explained below in Section 22.

are unique in this respect, and are called "lines of single wave velocity" or the "primary optic axes" or the "optic binormals."

In the same way if OU_2 and OU_2' be drawn perpendicular to the circular sections of the Fresnel ellipsoid (Figs. 305-307), the velocity of

any ray being given by the axes of the section perpendicular to it, and the section perpendicular to OU_1 being a circle, it is clear that OU_2 is a direction along which *rays* have only one velocity. The lines OU_2,

Fig. 307.—Circular Section of Ellipsoid.

OU_2', are consequently called the "lines of single ray velocity," or the "secondary optic axes" of a biaxial crystal.

Rays travelling along OU_2 do not have two definite planes of polarisation (since the circular section has not two definite axes) but may be polarised in any plane.

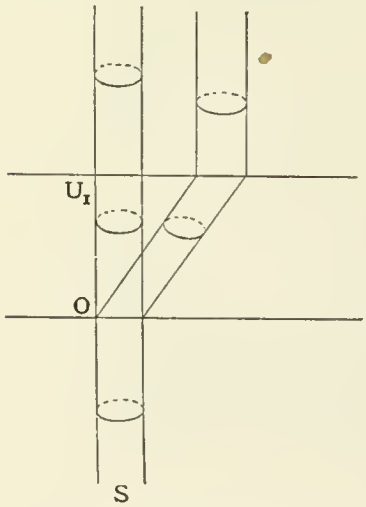


Fig. 308.—Primary Optic Axis or Optic Binormal.

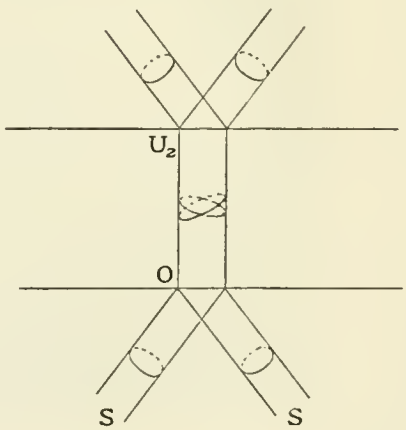


Fig. 309.—Secondary Optic Axis or Optic Biradial.

Neither a primary nor a secondary optic axis can be called a line of no double refraction in the exact sense in which the term optic axis was used for calcite on p. 130.

The behaviour of a beam of light travelling along these directions will be understood by comparing Figs. 308 and 309 with Figs. 300 and 301. Fig. 308 represents a plate cut perpendicular to a primary optic axis; light S incident in this direction will travel through the crystal in different directions as a cone of light (the figure is a section of the cone and shows two such directions) and emerge as a cylinder of parallel beams not polarised in two planes at right angles to each other. Fig. 309 represents a plate cut perpendicular to a secondary optic axis. All the rays belonging to the incident cone S travel in this direction through the crystal, and emerge as a cone of light whose rays are not polarised in two planes at right angles to each other.

Neither OU_1 nor OU_2 can be called exactly an axis of no double refraction; OU_1 most nearly possesses this property, and is generally called an optic axis of a biaxial crystal.

In almost all biaxial minerals the primary and secondary optic axes very nearly coincide, and there is no practical method of distinguishing between them, so that in future we shall be justified in speaking of the lines perpendicular to the circular sections of the indicatrix as the "optic axes." In a crystal of sulphur the angle between a secondary and primary optic axis is more than $3\frac{1}{2}°$, but this is quite exceptional, and the angle rarely exceeds a few minutes.

Moreover, in all known minerals a ray is so nearly perpendicular to its front that practically it is difficult to distinguish between a ray with its two vibration directions and the perpendicular to two parallel beam fronts with their two vibration directions.

17. **Uniaxial Crystals.**—When two of the axes in Fig. 304, say OA and OB, become nearly equal, the circular sections of the indicatrix become nearly horizontal and the two optic axes nearly coincide.

When OA and OB are actually equal, the plane AOB becomes the only circular section, the two optic axes coincide, and the indicatrix becomes an "ellipsoid of revolution," such as would be traced out by spinning the ellipse CB about the axis OC.

In the hexagonal and tetragonal systems, by virtue of the symmetry of the system, the axes OA and OB of the indicatrix must be equal, and the two optic axes coincide in the principal axis of the crystal; this line unites in itself the characters of the primary and secondary optic axes, and is a true optic axis or line of no double refraction; thus hexagonal and tetragonal minerals must be "uniaxial," and their optical characters are derived from an ellipsoid of revolution whose axis of symmetry is the principal axis of the crystal.

The planes of vibration and the refractive indices of the two plane-polarised beams of light which can be transmitted in any direction OP are the axes OL, OA, of the ellipse in which a plane perpendicular thereto intersects the indicatrix (Fig. 310). Only along the optic axis OC, which is perpendicular to the circular section, can plane-polarised light be transmitted polarised in any desired plane and with only one refractive index. In a uniaxial crystal any oblique section (AOL) has for one of its axes the radius AO of the circular section. Hence, of the

two beams which travel along any direction OP the one which is polarised in the principal plane POC and vibrates at right angles thereto always has the same refractive index; so that, as we have seen in the case of calcite, light transmitted obliquely consists in general of an ordinary and an extraordinary beam.

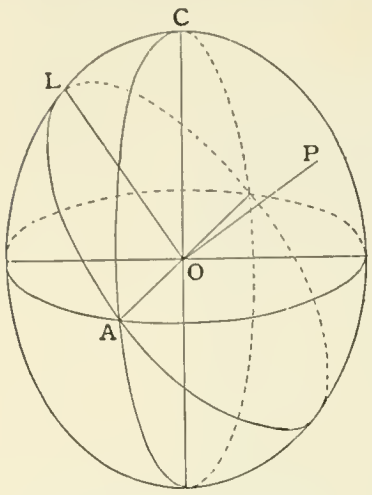


Fig. 310.—The Indicatrix of a (positive) Uniaxial Crystal.

In the cubic system, by virtue of the symmetry, all three axes of the indicatrix must be equal, and it becomes a sphere in which there are no unequal radii; the section of this sphere by a plane perpendicular to any ray is a circle. In a crystal of this system, accordingly, all rays travel with equal velocity, whatever their direction of vibration, and there is no double refraction. By virtue of their symmetry all cubic crystals must therefore be optically isotropic.

18. **Extinction.**—We have seen that when a slice cut out of any doubly refracting crystal is examined with parallel light between crossed nicols, there are four positions in which the section becomes dark as the stage is rotated. This is easily explained by means of the indicatrix.

The intersection of the indicatrix with the plane of the slice is an ellipse whose axes represent the vibration planes of the light traversing the plate perpendicularly.

Let Fig. 311 represent a crystal plate lying on the stage between the polariser, whose vibration direction is PP′, and the analyser, whose vibration direction is AA′. Let the ellipse, whose axes are OL, OM, be the intersection of the plate with the indicatrix of the crystal. Plane-polarised light issuing from the polariser enters the crystal vibrating in the plane OP. If OP does not coincide with OL or OM, the incident rays are divided in the crystal into rays vibrating in the planes OL and OM respectively.

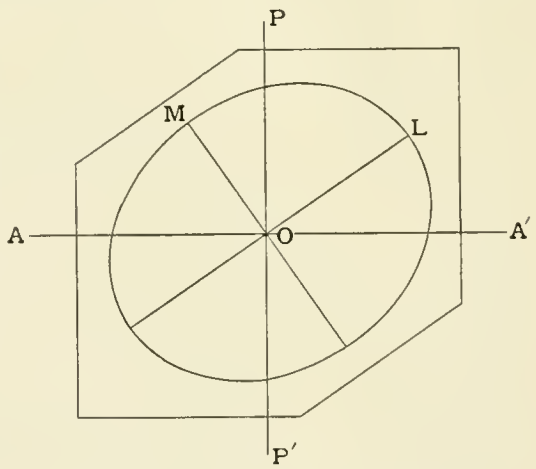


Fig. 311.—Extinction Lines of a Section.

Both these vibrations have a component along OA, so that some light is transmitted by the analyser. If, however, either OL or OM is parallel to OP, the plane-polarised light continues unchanged through the crystal, and is extinguished by the analyser.

The two positions in which the section becomes dark are therefore those in which its vibration planes coincide with the vibration planes (or shorter diagonals) of the nicols. These positions are called the "positions of extinction."

The lines OL, OM may be called the "extinction lines" of the crystal section. Every section must therefore have two characteristic extinction lines at right angles to each other and corresponding positions of extinction on the microscope stage.

A very important process in the optical identification of a mineral consists in finding the positions of extinction for different faces.

The angle made by one of the extinction lines of any face with a definite edge of the crystal is called the "extinction angle of the face." Thus the positions of the extinction lines when a crystal of diopside from Nordmark in Sweden is examined normally through a pair of prism faces are represented in Fig. 312. The angle which one of these lines makes with the prism edge is 36°; and this is said to be the "extinction angle" of the prism face of this diopside; the extinction angle on the clinopinakoid (010) is not the same but 46° 45′. The extinction angle of any section of a crystal is found in the following way.

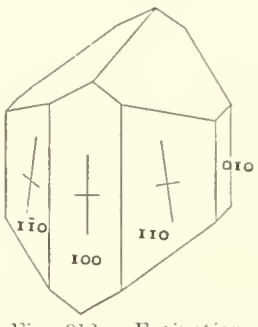


Fig. 312.—Extinction Angles of Diopside.

The crystal is laid flat upon a glass slide on the stage of the microscope, resting upon one of the two parallel faces under examination. The eye-piece of the microscope contains a pair of cross-wires so fixed as to be parallel to the vibration planes (*i.e.* the shorter diagonals) of the polariser and analyser; parallel light being used, the stage is first turned until the required edge is parallel to one of the cross-wires, and a reading is taken on the graduated circle. The stage is then turned until the crystal appears uniformly dark. In the first position, the cross-wire is parallel to the edge of reference; in the second position it is parallel to one of the extinction lines of the section. The angle through which the stage has been turned is the extinction angle of the section with reference to that edge. When an extinction is parallel to the edge of reference, the section is said to have "straight extinction" with regard to that edge. The face (100) in Fig. 312 has straight extinction.

When a face or section is parallel to a principal axis of the indicatrix, its extinction is also parallel to that axis, for when a plane section of the indicatrix passes through one of its axes, that axis is either the major or the minor axis of the elliptic section.

In the hexagonal, tetragonal and orthorhombic systems, one of the axes of the indicatrix always coincides with the vertical axis of symmetry of the crystal. Hence a prism face in any of these three systems has straight extinction.

The following is a very useful construction:—

In an ellipsoid to find the axes of any elliptic section OLM (Fig. 313), draw two planes through the line OP perpendicular to the section, one containing the optic axis OU, the other containing the optic axis OU′. Draw through the normal two other planes OLP, OMP bisecting the angles of the first pair, and therefore at right angles to each other; they will cut the elliptic section in its two axes, OL, OM.

Hence the extinction lines on any face or section are found by the same construction—made as follows on the stereographic projection.

Let P be the pole of the face or section—let U, U′ be the points on the sphere where the optic axes emerge (Fig. 314). Bisect the angle UPU′ internally and externally by planes which cut the sphere in the dotted circles; then these planes contain the extinction lines. Let Q be

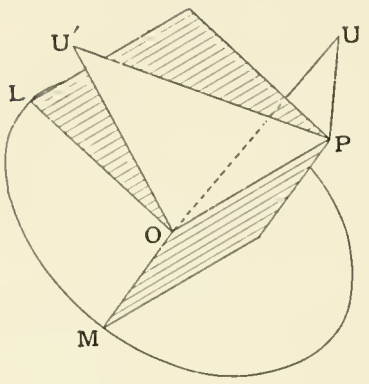


Fig. 313.—Extinction Lines and Optic Axes.

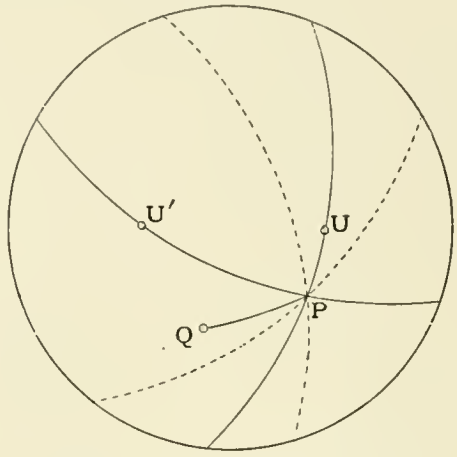


Fig. 314.—Extinction Angles and Optic Axes.

the pole of another face; then the extinction angle of P, taking the edge PQ as edge of reference, is the angle between one of the dotted circles and the arc PQ. From this construction it follows that in a uniaxial crystal, since U and U′ coincide, one of the extinction lines must always lie in the plane containing the optic axis and the normal to the section. This plane is called a "principal plane" of the crystal.

In accordance with this principle each face of the calcite rhombohedron of Fig. 289 must have extinctions parallel to its diagonals; for the shorter diagonal ZE lies in the principal plane, and the longer diagonal MN is perpendicular to it; for this reason also one of the images *o* and *e* was extinguished by the tourmaline plate, when its axis was either in the principal plane or perpendicular to it.

19. **Interference Phenomena—Parallel Light.**—We have seen that in general a section placed between crossed nicols, if not in a position of extinction, appears coloured, and that this colour varies with the thickness of the section.

Consider first an oblique section of a uniaxial mineral. When white light enters the plate normally, as in Fig. 315, it is doubly refracted; the ordinary beam continues its course unchanged through the section, since the incidence is perpendicular; the extraordinary beam is refracted, but on issuing from the section recovers its original direction, because it has been refracted through a plate with parallel faces. The transmitted light issues in the direction NP, but this light is a mixture of the two beams E and O. Now these two beams differ in one important particular: the ordinary beam has traversed a distance NP in the crystal, while the extraordinary beam has traversed a greater distance NP_1, and they have

travelled through the section with different velocities; consequently they emerge in different phases and would be in a position to interfere, were it not that they are polarised in two planes at right angles to each other.

Since the section is between crossed nicols (Fig. 311), the two emergent beams do not continue unchanged to the eye-piece of the microscope, but are sifted by the analyser; only that component of their vibrations which belongs to the direction OA is transmitted, and these two component vibrations, being executed in the same plane, are now capable of interfering.

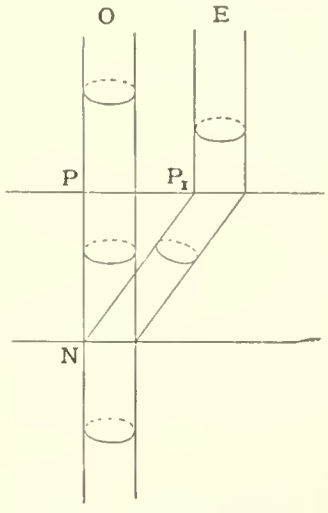


Fig. 315.—Oblique Section of a Uniaxial Crystal.

It must be noticed that the resolution by the analyser of two rays plane-polarised at right angles to each other introduces a *reversal* of phase; for a vibration in the direction OP (Fig. 311) is resolved into vibrations along OL and OM in the crystal, and of these OM is resolved in the analyser into a vibration along OA, but OL is resolved into one in the *opposite* direction OA′. Hence the analyser itself, like the internal reflection in Newton's rings, introduces a difference of phase of $\frac{1}{2}\lambda$ which must be added to that produced by the crystal.

If the section be examined by monochromatic light, such as the pure yellow light of a sodium flame, and if it be of such a thickness that the two beams which emerge differ in phase by a wave-length of that light, then the two rays will destroy each other and the plate will appear dark; if the thickness of the section be increased, light will be transmitted until it is just so thick that the difference of phase of the two rays on leaving the crystal is 2λ, when it will again appear dark, Generally, therefore, the section will appear dark when its thickness is such that the two rays differ in phase by any whole number of wave-lengths of sodium light.

Consider next the appearance presented by the crystal in white light which is composed of lights of different wave-lengths. A thin section will now transmit light of all colours except that which is annulled by interference. The result is that light of one colour being annulled, and other colours being transmitted, the section will appear tinted. In the case supposed, where the yellow rays are annulled, the crystal would appear purplish; the resultant colour must vary with the thickness of the section, and the strength of its double refraction. In an extremely thin section, or one with very weak double refraction, the difference of phase may be only a wave-length of violet light; in a thicker section, or one with stronger double refraction, it may be a wave-length of red light; hence, as the thickness or the double refraction increases, successive colours are extinguished, and the section changes in tint through a series of different colours; for differences of two wave-lengths a somewhat similar series of tints will recur, and again for three wave-lengths.

The order of succession of the colours must be nearly that of Newton's rings, since they are produced in a similar manner, by the loss of light of successive wave-lengths from white light. All that has been said above about the order of colours in Newton's rings will hold true here.

Many minerals may be distinguished from each other by these tints alone; thus in rock sections of the usual thickness (about 0·04 mm.) quartz, being a mineral of weak double refraction, "polarises" in the brilliant colours of the first order; calcite, a mineral of very strong double refraction, polarises in the dull gray tints known as "white of higher orders."

Since the colour varies with the strength of the double refraction, and the double refraction of a section depends upon its direction in the crystal, sections of the same thickness cut in different directions will also present different colours between crossed nicols.

20. **Interference Phenomena—Convergent Light.**—Consider first a plate cut from a uniaxial crystal perpendicular to the optic axis. The indicatrix is here an ellipsoid of rotation, and sections inclined at the same angle to the principal axis are similar ellipses; the double refraction continually diminishes from the direction perpendicular to the principal axis where it is as great as possible, to that parallel to the principal axis along which there is no double refraction; for in the latter case the axes of the corresponding section of the indicatrix are equal, while in the former they are as widely different as possible.

Let the adjoining figure (Fig. 316) represent a side view of the crystal

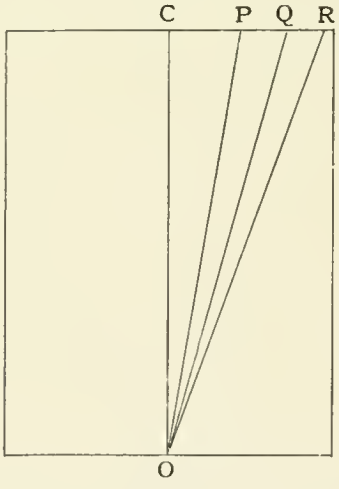


Fig. 316.—Interference in Uniaxial Crystal.

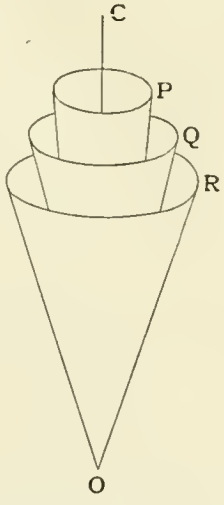


Fig. 317.—Interference in Uniaxial Crystal.

(which may be either hexagonal or tetragonal); then OC, the vertical axis, is also the optic axis. OP may be a direction in which for a plate of the given thickness the difference of phase for sodium light is λ; then all other directions with this inclination to OC will also correspond to a differenec of phase λ_{Na}.

Similarly all directions inclined to OC at the angle COQ may corre-

spond to a difference of phase 2λ; and those situated like CR correspond to a difference of 3λ, and so on. In passing from OP to OQ the difference of phase has been increased, not only owing to the greater double refraction but also to the longer path traversed by the more oblique rays in the crystal.

Hence in all such directions there will be darkness, and in all intermediate directions there will be light, when the plate is examined in convergent sodium light between crossed nicols.

Each set of directions forms a cone with circular base surrounding the optic axis (Fig. 317). The first cone represents all the directions in the crystal along which the birefringence is the same, and such as to produce a difference of phase of λ; the second 2λ, and so on.

For any other light or for any other thickness of plate the directions corresponding to differences of phase of λ, 2λ, etc., are also represented by circular cones about OC, but they will have a larger or smaller angle than those through OP or OQ of Fig. 317.

If white light be used each cone represents directions along which light of a certain wave-length is annulled, and therefore mixed light of a complementary colour is transmitted. A section of given thickness, cut perpendicular to any line such as OP in one of these cones will have the same colour when examined in white light between crossed nicols as a section of the same thickness cut perpendicular to any other line through O in the same cone.

The cones show the directions along which the double refraction is the same, and therefore also those in which the interference colours produced in convergent white light are the same for a plate cut perpendicular to the optic axis.

For biaxial crystals the same considerations hold true. Directions

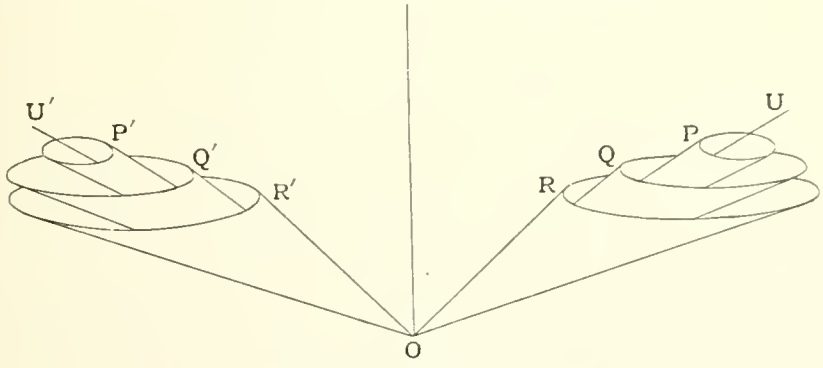


Fig. 318.—Interference in Biaxial Crystal.

along which the birefringence is very weak will nearly coincide with the optic axes UU′, but the cone containing directions whose birefringence is the same must be (by virtue of the lower symmetry of the crystal) no longer circular. The oval cone containing all directions along which the birefringence is such as to produce an interference of λ for a given thickness of crystal, being represented by P, there will be a similar cone P′ surrounding the other optic axis U′; and each of these will be succeeded

by larger cones with oval bases containing lines along which (for the same plate of crystal equally inclined to the two optic axes) the birefringence and length of path are such as to produce interference of 2λ, 3λ, etc.

The birefringence along each line is measured by the difference between the axes of the indicatrix section perpendicular to it.

The use of *convergent* light makes it possible to observe simultaneously the interference effects due to light travelling in many different directions through one and the same section. If the course of the rays through the microscope after they leave the crystal AB be traced, it will be seen that they are brought together again a short distance behind the objective. All the rays travelling parallel to the axis of the microscope

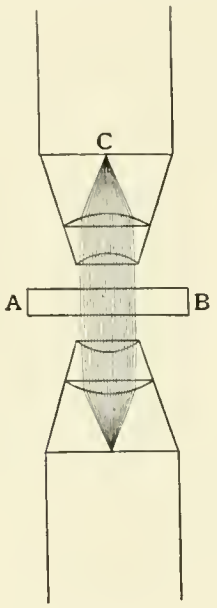


Fig. 319.

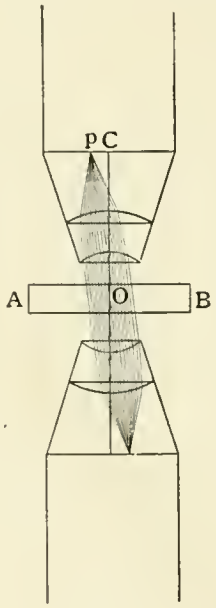


Fig. 320.

Figs. 319, 320.—Formation of an Interference Figure.

are brought to a focus at a point C on the axis (Fig. 319); all the parallel rays travelling through the crystal at a given inclination COp to the axis of the microscope OC are brought to a focus at a point p situated at a certain distance from C (Fig. 320). A beam of rays more inclined to the line OC converge to a point at a greater distance from C. The result is therefore to produce coloured bands, every different point of which is produced by rays having a certain different direction in the crystal. This effect may be seen, as stated on p. 133, either by removing the eye-piece or by introducing a lens at an appropriate distance above the objective or above the eye-piece.

In a slice cut perpendicular to the optic axis of a uniaxial crystal, the centre of the field of view will correspond to all the rays of light travelling along the optic axis, and will be a dark spot denoting a direction of no double refraction; this will be surrounded by a coloured circle corresponding to the cone of rays P of Fig. 317, and this again by successive

circles in which the colours follow the order of Newton's rings. Hence the interference figure seen in convergent light through this section will have the form of the curves in which the plane of the section cuts the cones of Fig. 317.

It was stated above that the circles of the uniaxial interference figure are intersected by a black cross; we have next to explain this feature.

Consider any point R in Fig. 321. Corresponding to this point are two rays, one vibrating in the "principal plane" RO, which contains the optic axis; the other vibrating perpendicular to that plane. These have each a component along OA, and are therefore resolved in the analyser into two rays which interfere and produce the colour corresponding to the cone through R.

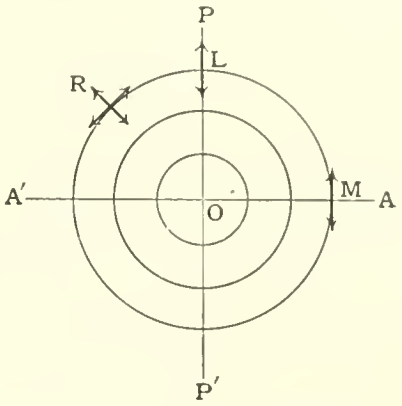


Fig. 321.—Uniaxial Interference Figure.

Now consider the light corresponding to any point L on PP'. This travels through the crystal as a plane-polarised ray vibrating in the principal plane (see p. 144), for it has no component perpendicular thereto,

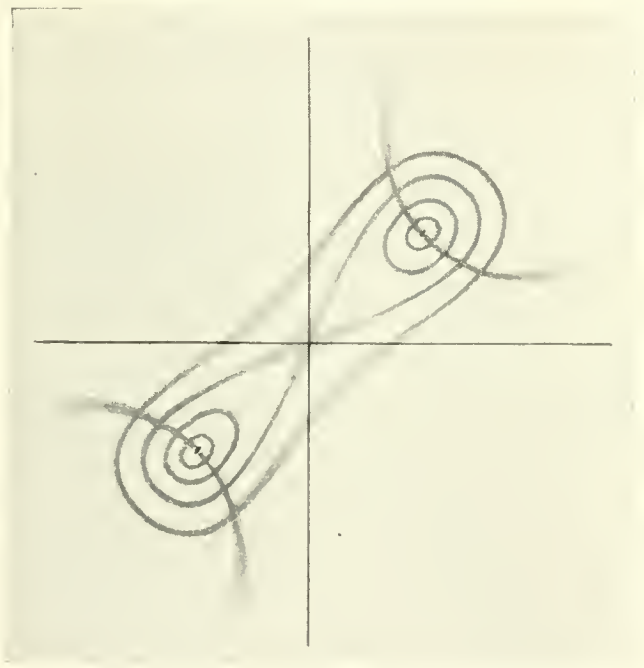


Fig. 322.—Biaxial Interference Figure; Diagonal Position.

and is therefore extinguished by the analyser; consequently any such point lying in the plane OP is one of darkness. Similarly the ray corresponding to M has no component along OA; it passes through the crystal, vibrating along OP alone, and is extinguished by the analyser; and this is true of any ray lying in the plane OM. Hence PP' and AA', the planes of polarisation and analysation in the microscope, become the two

arms of a black cross intersecting the circles of the uniaxial interference figure.

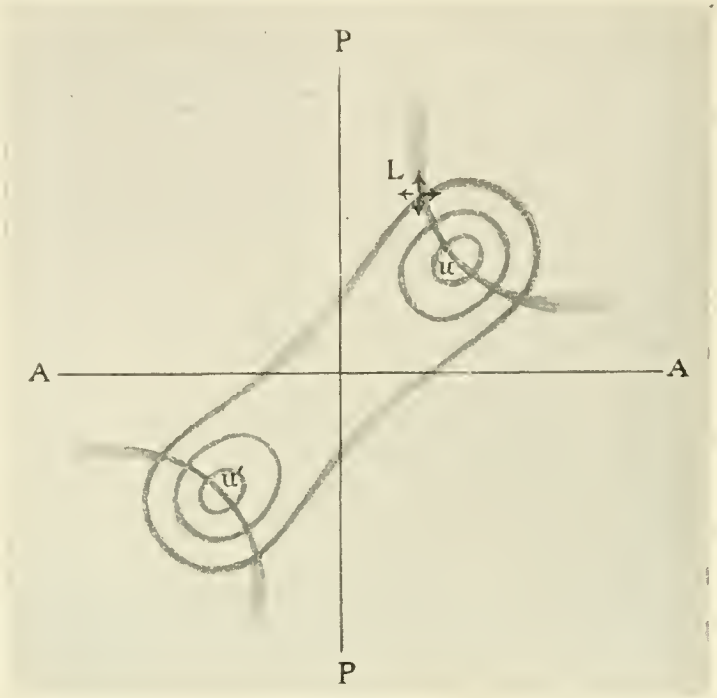


Fig. 323.—Retardation 2½ Wave-lengths.

In biaxial crystals the general form of the interference figures is indicated by the cones of equal retardation of Fig. 318, just as those of uniaxial crystals were suggested by Fig. 317.

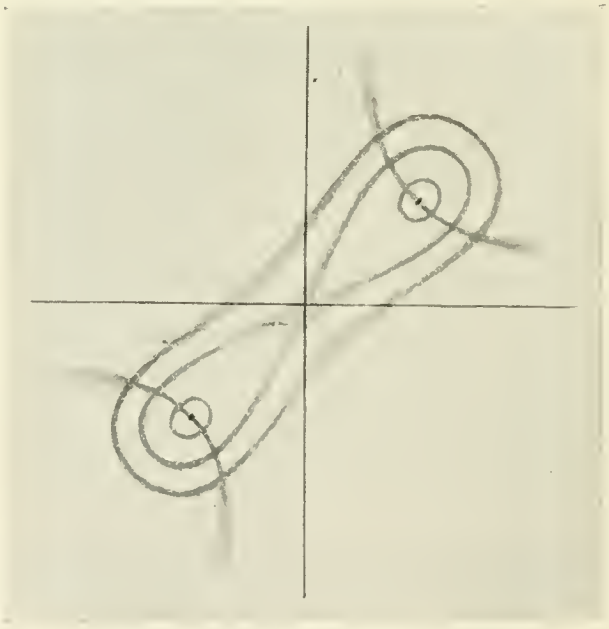


Fig. 324.—Retardation 2 Wave-lengths.

A section equally inclined to the two optic axes will exhibit two dark spots u, u' Fig. 323, corresponding to the optic axes, and

these will be surrounded by coloured oval rings. The rings are approximately the curves known as lemniscates ; the first few rings will generally

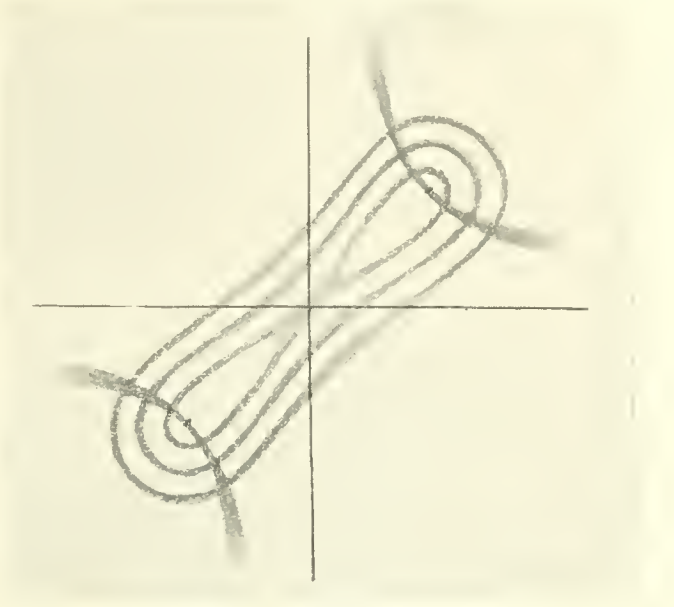


Fig. 325.—Retardation 1 Wave-length.

form ovals surrounding the optic axes; a later pair may join at the centre in a figure of 8, and the subsequent rings will form continuous curves.

The effect of reducing the thickness of a section may easily be

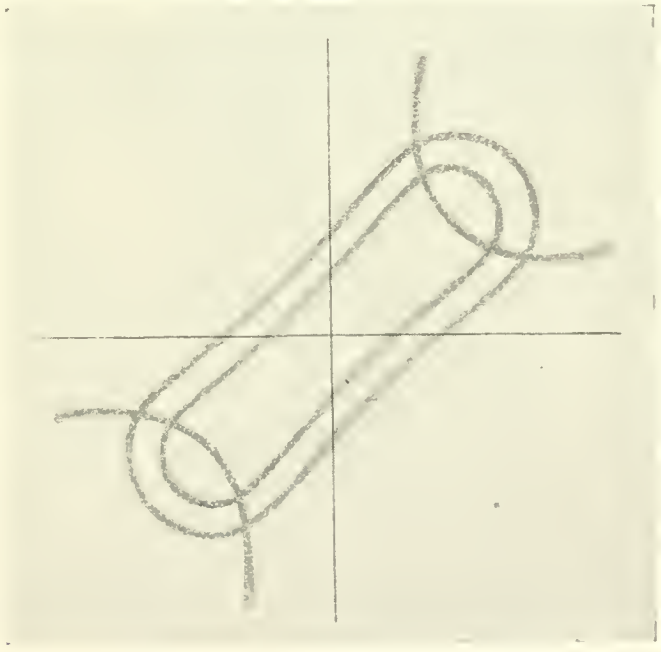


Fig. 326.—Retardation ½ Wave-length

observed by cleaving a plate of mica successively into thinner and thinner sheets, and is shown in Figs. 322-326.

As in a uniaxial, so also in a biaxial crystal the rays must travel more obliquely in order to produce a given retardation in a thin section than in a thicker one, and the rings are consequently larger.

An optic axis will no longer be intersected by a black cross. There are, however, certain dark bands which correspond to the black cross of the uniaxial figure. The crystal being turned through 45° from the position of extinction, for some point L in the figure the directions of vibration (found, as described above, by bisecting the angles between two planes containing the ray L and the optic axes) may prove to be parallel to OP and OA (Fig. 323). Wherever this is the case darkness will result, for the same reason as at the point R in Fig. 321. The total assemblage of such points constitutes the two arms of a hyperbola—one

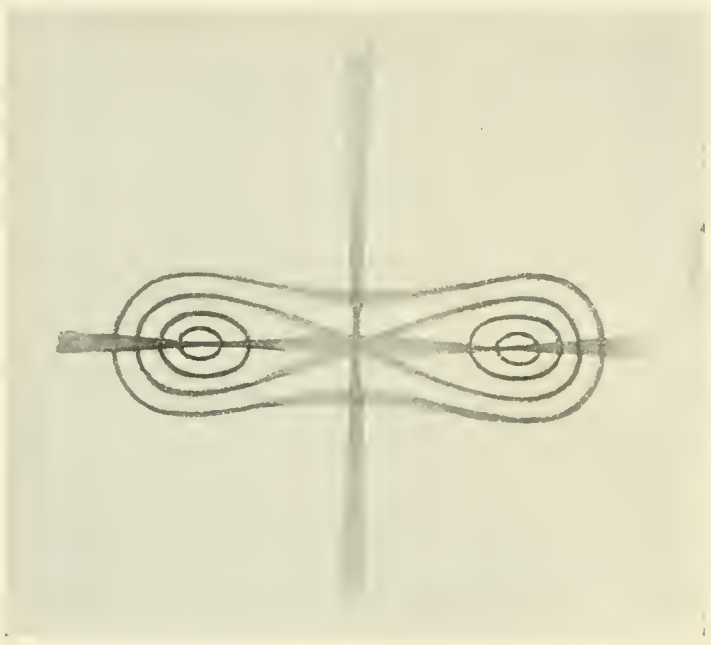


Fig. 327.—Biaxial Interference Figure; Extinction Position.

of these passes through one optic axis, u, and the other through the other, u'; but these points will not lie upon PP′ or AA′ unless the optic axes themselves lie upon one of those lines, and the hyperbola then becomes a cross (Fig. 327). Hence, as the section is rotated with the stage, the optic axes rotate with the crystal round the centre, but the interference figure changes from that shown in Fig. 327, in which the dark bands or "brushes" form a cross, to that of Fig. 322, in which they are the two branches of a hyperbola. In the former position the plane of the optic axes coincides either with PP′ or AA′. The latter position, where the plane of the optic axes is inclined at 45° to AA′ and PP′, is called the "diagonal position."

21. **Axial Angle. Bisectrices.**—The optic axes in a biaxial crystal are inclined to one another at some angle which is called the "optic axial angle." As observed in air by the microscope, the optic axes appear to include a considerably larger angle, since light travelling

along them is refracted out of the crystal with a greater divergence, as shown in Fig. 328.

The angle between the two lines UU′ is called the "true axial angle"; it is the angle between the optic axes inside the crystal, and is represented by the symbol 2V; but the angle observed in the microscope is that between the lines u and u' as refracted outside the crystal; this is called the "apparent axial angle in air," and is denoted by the symbol 2E.

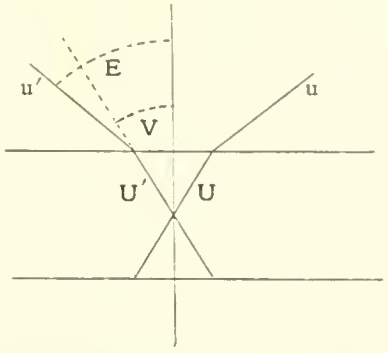


Fig. 328.—Apparent Axial Angle.

The apparent axial angle may be conveniently and approximately estimated by means of a micrometer placed below the eye-piece; each division on the micrometer corresponds to rays of certain obliquity, and the apparent angle may therefore be estimated by the number of divisions between the optic axes. The micrometer may be approximately calibrated by means of crystals of known axial angles. The manner in which the optic axial angle can be accurately measured is described on p. 177.

The section has been hitherto supposed to be cut perpendicular to the line bisecting the acute angle of the optic axes; if it be cut perpendicular to the line bisecting the obtuse angle, a portion of the ring system may be visible, as may be seen from a consideration of Fig. 318, but the rays corresponding to the optic axes themselves are now so widely divergent that in general they either are totally reflected internally, or are refracted out at an apparent angle so large that it exceeds the limits of the field of view.

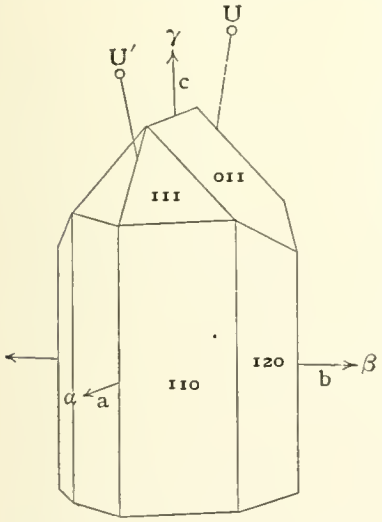


Fig. 329.—The Optic Axes of Topaz.

Of the three axes of the indicatrix for a given colour, one must coincide with the line bisecting the acute angle of the optic axes; this is called the "acute bisectrix" or the "first mean line." A second axis bisects the obtuse angle between the optic axes, and is called the "obtuse bisectrix" or "second mean line." The third, which must always be the mean axis OB, the vibration direction of light giving the index of refraction β, is perpendicular to the plane of the optic axes, and is called the "third mean line." Fig. 329 represents these lines in a crystal of topaz in which the vertical crystal-axis c is the acute, and the brachy-diagonal a the obtuse, bisectrix.

It is evident that the optic axes will generally be visible through a sufficiently thin section cut perpendicular to the acute bisectrix. A ring system without the optic axes will be visible in a section cut perpendicular to the obtuse bisectrix, while neither optic axes nor ring

system, but only curved black bands will be visible in monochromatic light in a section cut perpendicular to the third mean line.

When the section is perpendicular to the second mean line, although the optic axes may not be visible, the hyperbolic brushes will be seen to meet symmetrically in a cross *at the centre of the field*, and to separate again into a hyperbola as the stage is rotated. This will not be the case with a section cut obliquely to a mean line. Even when the optic axis of a uniaxial, or the two optic axes of a biaxial, crystal are not completely visible, their position may be approximately determined by the portion of the interference figure which falls within the field of view.

The accompanying diagrams (Figs. 330, 331) show the manner in which portions of the interference figure may be visible, and may enable the observer to construct the remainder of the figures, as indicated outside the circle which represents the field of view of the microscope.

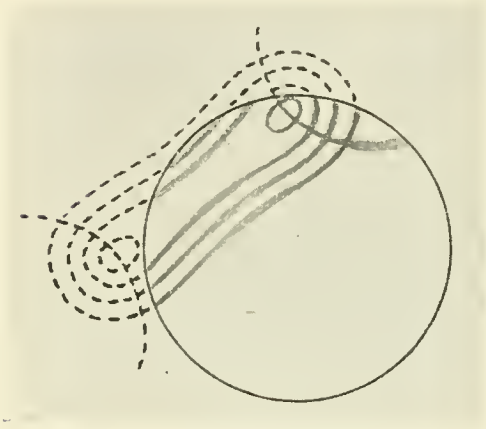


Fig. 330.

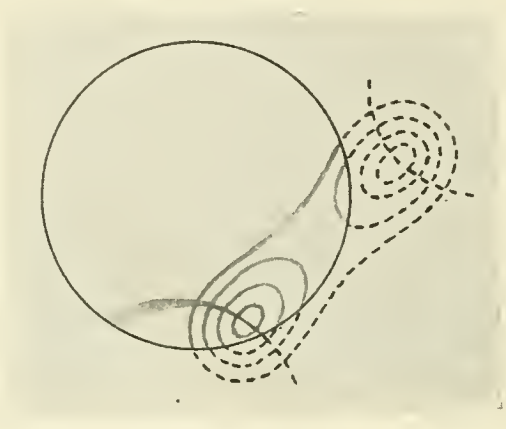


Fig. 331.

Figs. 330, 331.—Interference Figures of Sections cut obliquely to the Acute Bisectrix.

The optic axis of a uniaxial crystal may always be distinguished from an axis of a biaxial crystal, since the former is intersected by the *two* arms of a black cross, the latter by only *one* branch of the hyperbola.

22. **Sign of the Double Refraction.**—In a uniaxial crystal the optic axis may be either the major or the minor axis of the indicatrix; in the first case the indicatrix is a prolate ellipsoid resembling an egg; in the second it is an oblate ellipsoid resembling an orange. Similarly in a biaxial crystal the acute bisectrix may be either the greatest or the least axis of the indicatrix.

Figure 310 represents the indicatrix of a uniaxial crystal in which OC, the optic axis, is the major axis; then light whose direction is OP consists of two sets of rays vibrating in the planes AOP and LOP. Of these two, whatever may be the direction of OP, one always vibrates along a radius of the ellipsoid equal to OA; such rays travel with the same velocity and are equally refracted; they are therefore the ordinary rays. OA then is the ordinary index of refraction, and OL the extraordinary index of refraction of the light whose direction is OP.

Now OA is a minor axis of the ellipsoid. OL is therefore greater than

OA, and any extraordinary index of refraction in such a crystal is always greater than the ordinary index.

Such a crystal is said to have "positive birefringence." Its optic axis is the vibration-direction of light corresponding to the greatest possible refractive index in the crystal.

In other uniaxial crystals the optic axis may be the vibration-direction for the least possible refractive index, and any extraordinary index is therefore less than the ordinary. Such crystals are said to have "negative birefringence."

Using the symbol ω for the ordinary and ϵ for the principal extraordinary index of refraction, the sign of the birefringence is that of $\epsilon - \omega$. In a positive crystal, like quartz, the extraordinary index is greater than the ordinary. In a negative crystal, like calcite, the extraordinary index is less than the ordinary.

By analogy, the same terms are used to distinguish between the two sorts of biaxial crystals; those whose *acute bisectrix* is the greatest axis of the indicatrix, *i.e.* the vibration-direction of light corresponding to the refractive index γ, are called *positive crystals;* those whose *acute bisectrix* is the least axis of the indicatrix, or vibration-direction of light corresponding to the least index of refraction α, are called *negative crystals.*

Figs. 303, 304 show that the indicatrix of a positive biaxial crystal approximates in form to that of a positive uniaxial crystal; similarly, those of uniaxial and biaxial negative crystals resemble one another in form.

The manner in which the sign of a crystal is determined practically is described on p. 170.

It sometimes happens that a section can be seen from its interference figure to be perpendicular to a bisectrix, but it is not known whether it is the acute or the obtuse bisectrix; it is only certain that the third mean line must lie in the plane of the section. In such a case, however, if the perpendicular to the section is a radius of the indicatrix which is greater than the third mean line, it is known to be a *positive bisectrix;* if it is less than the third mean line it is known to be a *negative bisectrix.*

23. **Dispersions of the Optic Axes and Bisectrices.**—It was said above that the indicatrix for light of one colour is not the same as that for light of another colour in any crystal; hence the optic axes of a biaxial crystal may have different positions for different colours. This is known as the "dispersion of the optic axes." Yet, owing to the cardinal principle that the geometrical symmetry planes are also planes of symmetry for the physical characters, the dispersions in the orthorhombic and the monoclinic systems are of different sorts.

Orthorhombic System.—Here the three axes of symmetry of the indicatrix must coincide with those of the crystal, whatever the colour of the light, and therefore the axes of the indicatrix must coincide with the axes of the crystal. Hence one crystal axis must be the acute bisectrix, a second the obtuse bisectrix, and the third must be the third mean line. On the other hand, the positions of the optic axes may vary, so long as

they lie somewhere in the planes of symmetry; the axial angle for one colour may be larger than the axial angle for another colour.

When the axial angle for red light is greater than that for blue light, the interference figure seen by monochromatic red light (*e.g.* the flame of a lithium salt) may be that indicated by the continuous lines in Fig. 332, while the figure in monochromatic blue light occupies the position of the dotted lines. S and S′ are the two symmetry planes of the crystal. The interval RR′ is greater than BB′.

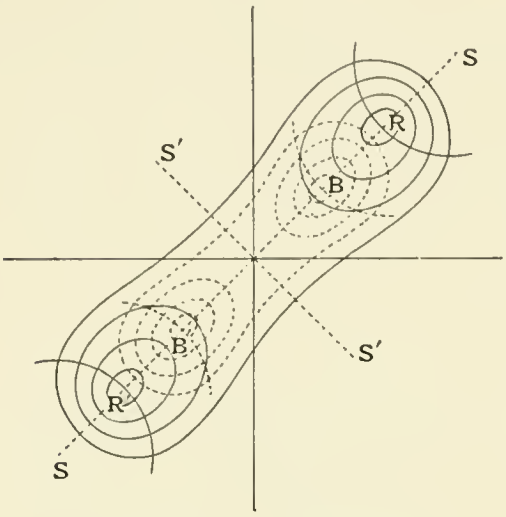


Fig. 332.—Dispersion of the Optic Axes.

In white light the figure will be that resulting from the superposition of all such monochromatic figures. The hyperbolic brush will on the whole occupy the region between B and R, but will be fringed with colour; at the point B, where the blue light is extinguished, it will be reddish; at the point R, where the red light is extinguished, it will be bluish. Hence when the axial angle for red is greater than that for blue, the hyperbola will appear red on its convex side in the neighbourhood of the optic axes; *i.e.* the red portions will lie closer together than the blue portions.

On the other hand, when the axial angle for red is less than that for blue, the effect is reversed; red light is extinguished at two points, which are closer together than those at which blue light is extinguished. The hyperbolic brushes are blue on their convex, and red on their concave side (Plates I., II.).

When the axial angle for red is greater than that for blue the character is expressed thus, $\rho > v$; when the axial angle for red is less than that for blue it is expressed $\rho < v$.

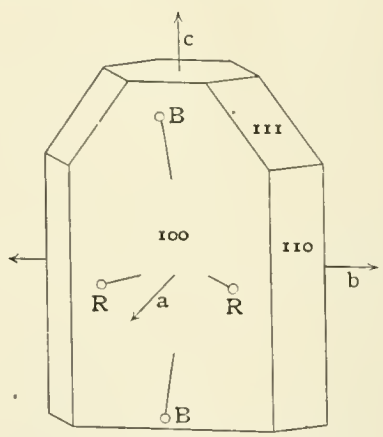


Fig. 333.—Crossing of the Optic Axial Planes in Brookite.

There is one other mode of dispersion possible in the orthorhombic system. One crystal axis, for example *a* in Fig. 333, may be the acute bisectrix, but the optic axes for *red* may lie in one symmetry plane, *e.g.* (001), while the optic axes for *blue* lie in the other symmetry plane (010). This does not violate the symmetry of the system. In this case, if lights of different colours in the order of increasing wave-length are successively employed, the interference figure changes. With monochromatic blue light the figure is as shown in the dotted lines of Fig. 334; with red light, as in the continuous lines; and since the transition is gradual as light of increasing wave-length is employed, the optic axes close up to the bisectrix

along RR and then open out at right angles to this along the line BB. For some intermediate colour, such as green, the crystal is uniaxial. But it is easily distinguished from crystals belonging to the hexagonal or tetragonal systems, since these are uniaxial for *all* colours.

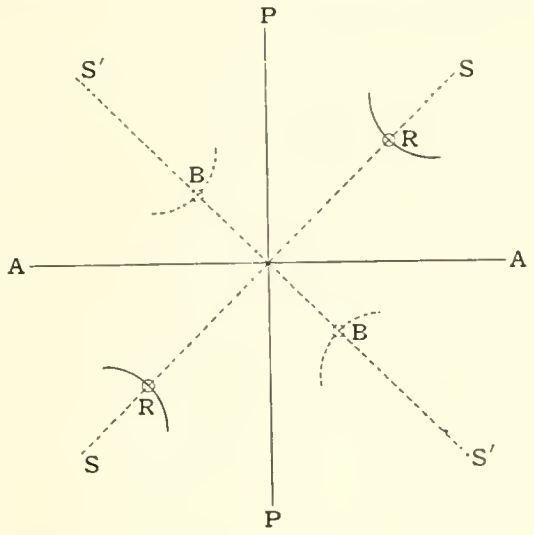


Fig. 334.—The Interference Figures of Brookite.

This mode of dispersion is remarkably exemplified by the mineral brookite, diagrammatically represented in Fig. 333. Such a mineral is said to have the "planes of its optic axes crossed."

The essential and characteristic feature of the interference figures of all orthorhombic crystals is their symmetry about the two lines SS and S′S′.

Monoclinic System.—Here, in addition to the dispersion of the optic axes, the crystal may also present a "dispersion" of one or both of the bisectrices; for it is no longer necessary that they should both coincide with crystal axes, but the bisectrices for different colours may occupy different positions. The plane of symmetry must coincide with one of the axial planes of the indicatrix; in other words, the axis of symmetry, *i.e.* the crystal axis *b*, must coincide with one of the axes of the ellipsoid. The three possible cases are those in which the *b* axis coincides respectively with the acute bisectrix, the obtuse bisectrix, and the third mean line.

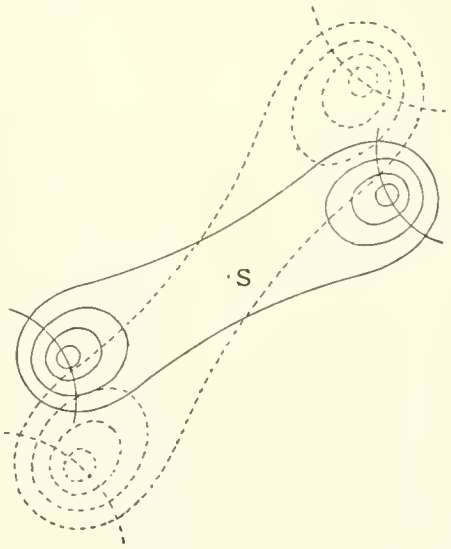


Fig. 335.—Crossed Dispersion.

(1) *Crossed Dispersion*—Axis of Symmetry, the Acute Bisectrix.—Here the centre of the figure is an axis of symmetry. The optic axes may lie in different planes, all passing through this axis. Fig. 335 shows a possible

disposition of the axes: the axes for red occupy a different position from those for blue (dotted); each pair is symmetrical about the bisectrix S. Hence the interference figure in white light will have no line of symmetry but is symmetrical about its centre. This is well illustrated by borax, whose interference figure displays colours which are always the same at equal distances on opposite sides of the bisectrix but have no other symmetry.

(2) *Horizontal Dispersion*—Axis of Symmetry, the Obtuse Bisectrix.—Here the optic axial planes are, as before, a series of planes intersecting in the axis *b*, but they are now viewed along the plane of symmetry S, not along the axis *b*; consequently the axes for different colours must be situated, as in Fig. 336, so as to be all symmetrical to the plane S. The interference figure in white light has one line of symmetry, S, perpendicular to the line joining the optic axes. This is illustrated by

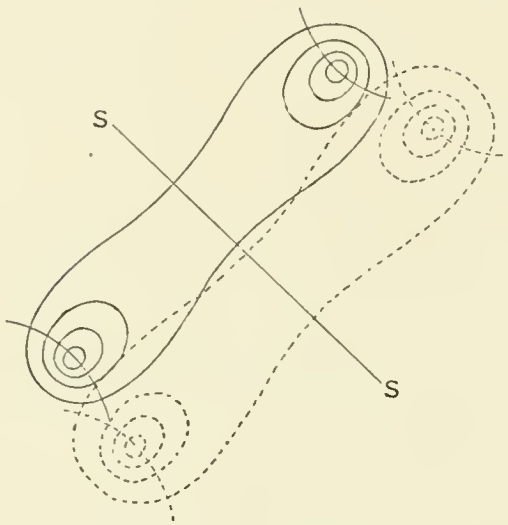


Fig. 336.—Horizontal Dispersion.

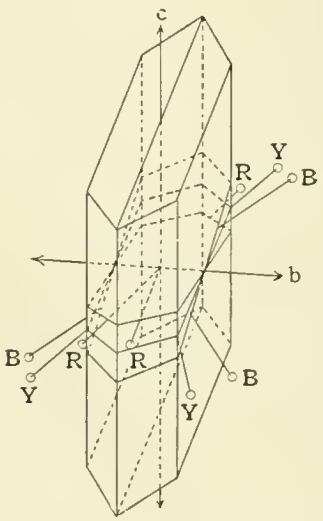


Fig. 337.—Crossed and Horizontal Dispersions.

some varieties of adularia felspar, in which the disposition of the interference colours is symmetrical about the line perpendicular to the axial plane. Fig. 337 illustrates both these dispersions, and indicates that a crystal which shows crossed dispersion about its obtuse bisectrix must show horizontal dispersion about the acute bisectrix, and *vice versâ*.

(3) *Inclined Dispersion*—Axis of Symmetry, the Third Mean Line.—Here the optic axial plane is the plane of symmetry. The axes may lie as in Fig. 338; both the optic axes and the bisectrix may be dispersed in any direction in the plane of symmetry. Hence the figure as seen in white light has only one line of symmetry, joining the optic axes (see Fig. 338 and Plate II.). In this case the dispersion is often recognisable, not only by the symmetry of the colours but also by the difference of size of the rings about the two optic axes (Fig. 338).

In the above dispersions a line of symmetry in the interference figure shows the direction of the corresponding plane of symmetry in the crystal, and a point of symmetry that of an axis.

As in the orthorhombic system, there are also in the monoclinic system crystals in which the axial plane for one colour is at right angles to that for another; thus the obtuse bisectrix for blue may coincide with *b* (Fig. 337), the axes for red may lie in the plane of symmetry, those for blue lying in a plane perpendicular to the same, and for some inter-

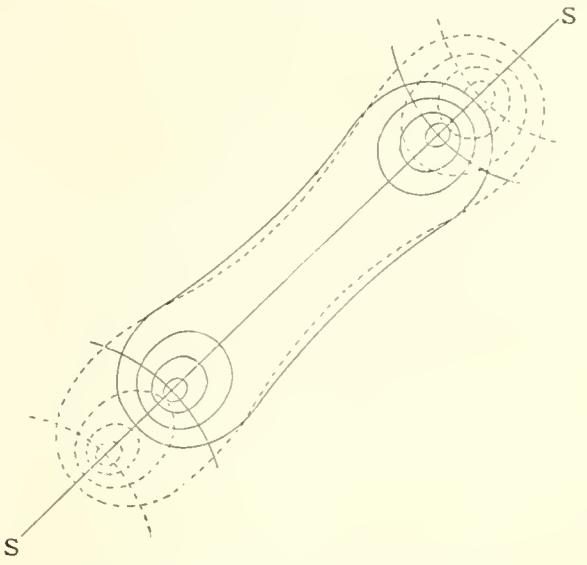


Fig. 338.—Inclined Dispersion: cf. Plate II.

mediate colour the crystal will be uniaxial, the optic axis lying in the plane of symmetry.

Anorthic System.—The dispersions of the optic axes and of the bisectrices may here be in any directions; consequently the interference figure for white light does not necessarily possess any symmetry.

24. **Absorption of Light—Pleochroism.**—We have seen above that a section of coloured tourmaline cut parallel to the axis transmits only light which we may regard as vibrating along the axis; the other ray is completely absorbed. It is evident, then, that the absorption of light depends upon the direction in which the light vibrates within the crystal.

Although few minerals possess so marked a difference of absorption as tourmaline, in which one ray is completely absorbed when the crystal is sufficiently thick and deeply coloured, many possess the property in a less degree, so that light of a given colour is more absorbed when polarised in one plane than when polarised in another. Now the plane of polarisation of transmitted light varies with the direction of transmission; hence in such crystals, if white light be employed, the colour of the crystal will appear different, according to the direction in which the light is transmitted.

This property, which is called "dichroism," or more generally "pleochroism," is especially marked in the case of cordierite, a mineral which is also known by the name of dichroite in allusion to this change of colour. A crystal of cordierite held up to the light and viewed in one direction appears bluish; in another direction it appears yellowish. The character is one of considerable importance in distinguishing between several of the

precious stones. Sapphire, ruby, and chrysoberyl are distinctly pleochroic. The property is also one of importance in the recognition of minerals in the microscopic sections of rocks.

There are two ways of examining the pleochroism.

The two plane-polarised beams which can traverse the crystal in a given direction are differently absorbed: in one beam, light of one colour is the most absorbed; in the other beam, light of some other colour is the most absorbed. When they emerge from the crystal they will be differently coloured, and the two rays may either be observed successively or simultaneously; they are observed successively under the microscope (see p. 176); they are observed simultaneously by means of the dichroscope.

The dichroscope consists simply of a long cleavage rhomb of calcite P (Fig. 339) mounted in a tube which has a small square aperture at one end A, and at the other a lens B, by which the aperture is viewed through the calcite and magnified. Owing to its strong double refraction the calcite produces two distinct images of the aperture, and the length of the rhomb is chosen so that the two images are seen side by side without overlapping. The ordinary image occupies the centre of the field of view, and is due to vibration along the longer diagonal of the prism; the extraordinary image is deflected (p. 129), and is due to vibration along the shorter diagonal.

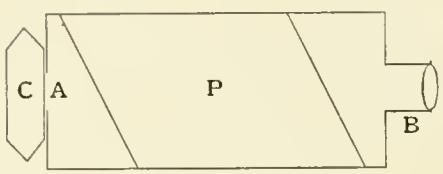


Fig. 339.—The Dichroscope.

In using the dichroscope it is only necessary to direct the instrument towards a window or other source of white light, to hold the crystal or section (C) in front of the small square aperture and turn it round until the two images are as differently coloured as possible.

A crystal of the orthorhombic cordierite (Fig. 340) examined in different directions by the dichroscope shows the following colours.

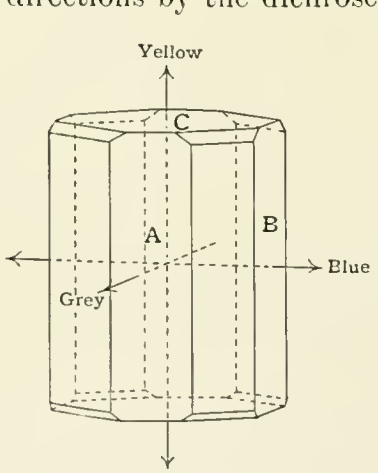


Fig. 340.—Cordierite.

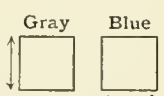


Fig. 341.—The Axial Colours of Cordierite viewed through C.

When the light is due to vibrations taking place parallel to the macro-diagonal it is deep blue; when vibrating parallel to the brachy-diagonal it

is grayish blue; while that vibrating parallel to the vertical axis is yellow. Hence viewed through the basal plane the colours of the two dichroscope images are gray and blue (Fig. 341); viewed through the brachy-pinakoid the two colours are grayish blue and yellow; viewed through the macro-pinakoid they are blue and yellow. Each face is *dichroic*; the crystal as a whole is *pleochroic*.

These colours are called the "axial colours." Viewed by ordinary light without the dichroscope, the colour transmitted by the basal plane will be a blue which is a mixture of the two axial colours belonging to the macro- and brachy-diagonals; similarly the colour of the brachy-pinakoid will be a yellowish-green; that of the macro-pinakoid bluish-green.

These mixed colours, due to the combination of the axial colours and seen when the crystal is viewed by ordinary light, are called the "face colours."

25. **Rotatory Polarisation.**—A remarkable property possessed by crystals of quartz is the power of rotating the plane of polarisation of light transmitted in the direction of the principal axis. As is well known, this rotatory property is also possessed by the solutions of certain organic substances, such as sugar and tartaric acid, which crystallise in enantiomorphous forms and possess an unsymmetrical chemical constitution; but the property was discovered first in quartz.

Rays of plane-polarised light incident on a plate of quartz in the direction of the optic axis emerge as plane polarised light, but the plane of polarisation has been rotated about this direction through an angle which depends upon the thickness of the plate and upon the colour of the light.

The angle of rotation is proportional to the thickness of the crystal and is nearly inversely proportional to the square of the wave-length of the light.

The angle of rotation in quartz for each millimetre of thickness is approximately

Red light	(Line A) . . .	13°
Yellow light	(„ D) . . .	22°
Blue light	(„ F) . . .	33°

In the annexed diagram (Fig. 342), if P be the direction of vibration in the polariser and A that in the analyser, the directions of vibration of the red, yellow and blue light, after passing through a basal section of quartz six millimetres in thickness which rotates the plane to the right (*i.e.* in the direction of a clock-hand), will be represented by the lines R, Y, and B respectively. Consequently, if daylight be used, the only light extinguished will be the blue, whose direction of vibration is nearly perpendicular to A; a certain proportion of the red and yellow light will be transmitted and the section will appear orange. Now let the analyser be turned to the right (or in the direction of a clock-hand), the colours will be extinguished in the order red, orange, yellow, green, and the section will appear green, changing to blue, purple, and red with the rotation of the analyser.

Some crystals of quartz rotate the plane of polarisation to the right; others rotate it to the left.

Thus in a dextro-rotatory or right-handed quartz crystal, a right-handed rotation of the analyser will cause the section to assume a succession of vivid tints which pass from blue to red through purple.

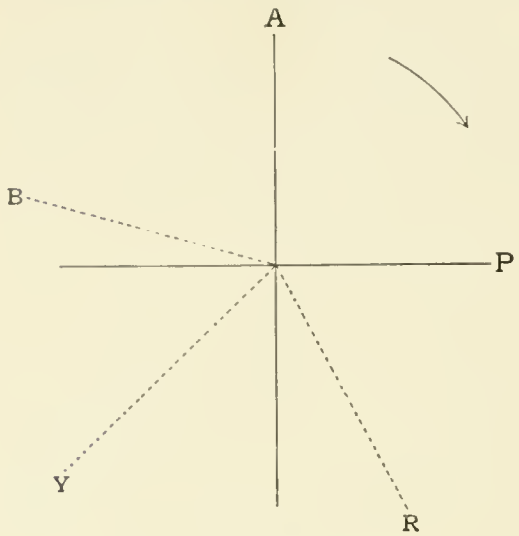


Fig. 342.—Rotatory Polarisation.

In a left-handed quartz crystal the same succession of tints is produced by a left-handed rotation of the analyser; in this way it is easy to distinguish between the two sorts of crystals.

Examined between crossed nicols in convergent light the section will give the ordinary uniaxial interference figure, with the exception that the centre of the field is occupied not by the centre of a black cross but by a patch of colour (Fig. 343) corresponding to the light which has traversed the crystal along the principal axis, the tint depending upon the thickness of the section; and this central patch of course changes tint, as just explained, when the analyser is rotated.

It was shown by Brewster and Herschel that the rotatory polarisation is intimately related to the crystalline form. A quartz crystal which is optically right-handed is also right-handed in the crystallographic sense used on p. 75. Of the two enantiomorphous crystals of quartz shown in Figs. 192, 193, one (Fig. 192) is optically right-handed, the other (Fig. 193) is optically left-handed.

The only other mineral known to show rotatory polarisation is cinnabar, which possesses a rotatory power more than thirteen times as great as that of quartz. Cinnabar also belongs to the Quartz class of crystals.

Several other uniaxial substances, however, possess the same power, not only rhombohedral, as calcium thiosulphate, strontium thiosulphate and sodium periodate, but also tetragonal, as quinine sulphate.

Fig. 343.—Interference Figure of Quartz.

In addition to these, certain crystals belonging to the cubic system, such as sodium chlorate and sodium bromate, also rotate the plane of polarisation; in the uniaxial crystals the rotatory polarisation can only be observed in the direction of the optic axis, but in those of the cubic system plane-polarised light is rotated through an angle depending

upon the thickness of crystal traversed, whatever the direction of the light. In this respect, therefore, an optically active cubic crystal behaves exactly like an optically active solution.

These substances all resemble quartz in crystallising in enantiomorphous forms, and of the two supplementary crystals one is always right-handed and the other left-handed in the optical as well as the crystallographic sense.

It has generally been supposed that all enantiomorphous crystals belonging to the cubic or uniaxial systems are optically active, and conversely that all optically active crystals must be enantiomorphous. This, however, has not been proved, for cuprite, sal-ammoniac and barium nitrate do not rotate the plane of polarisation, and there is no evidence that calcium and strontium thiosulphates are asymmetrically hemihedral.

26. **The Optical Constants.**—In order to define accurately for any mineral all the "crystallo-optical" characters which have been described above, and to express them in numbers, it is necessary to know the axes of the indicatrix for different colours, and the positions which they occupy in the crystal. When the relative lengths and the directions of the axes of this ellipsoid have been determined for light of any one colour, then the refraction, the double refraction, all the extinction directions and the optic axial angle for that colour can be accurately deduced. When, further, the relative positions of the ellipsoids for different coloured lights have been determined, the dispersions of the optic axes and of the bisectrices are also known.

Now the axes of the indicatrix for a certain colour are simply $OA = \alpha$, $OC = \gamma$ (the minimum and maximum refractive indices for that colour) and $OB = \beta$, the refractive index common to rays transmitted in different directions in the plane AOC, Figs. 304, 306.

The main constants to be determined are therefore the three indices of refraction for light polarised in the planes BOC, COA, AOB; or, to use the language employed above, for light vibrating along OA, OB, OC.

These three indices of refraction are called the three "principal indices" of the crystal.

In the monoclinic system the directions of the indicatrix-axes are defined by stating which pair lies in the plane of symmetry (010), and what is the angle between one of them and the vertical crystal axis c. If this indicatrix-axis is situated in the obtuse angle of the crystal axes ac, its inclination to c is called positive; if in the acute angle it is negative.

The absorption of light in a crystal is also described by reference to the same three lines; for this purpose it is only necessary to state the colour of the light vibrating along each of the three axes, and the relative magnitude of the absorption. Thus the absorption of cordierite is completely defined as follows: "$\alpha = c$, $\beta = a$, $\gamma = b$," which gives the position of the axes; "α yellow, β gray, γ blue," which gives the axial colours; "absorption for $\gamma >$ absorption for $\beta >$ absorption for α," which gives the magnitude of the absorption. It will be remembered

that the relative magnitudes of the refractive indices themselves are always $\gamma > \beta > \alpha$.[1]

Similarly, for a uniaxial crystal, such as tourmaline, reference is made to the ordinary and the extraordinary indices ω and ϵ (*e.g.* for tourmaline absorption for $\omega >$ absorption for ϵ).

There does not seem any reason that in biaxial crystals (except in the orthorhombic system) the principal axes of absorption should coincide with the axes of the indicatrix, which are merely characteristic of refraction; indeed, in the case of epidote it has been proved that they do not coincide; but the former are difficult to discover, so that the character of the absorption is generally expressed by reference to the axes of the indicatrix.

The following two examples, beryl as a uniaxial, and diopside as a biaxial mineral, show how the optical constants may be conveniently described.

Beryl (Fig. 169).—Birefringence negative, weak.

	Red (Li).	Yellow (Na).	Green (Tl).
ω	1·586	1·589	1·592
ϵ	1·579	1·582	1·584
$\epsilon - \omega$	− ·007	− ·007	− ·008

Absorption weak, $\epsilon > \omega$; ϵ bluish, ω green.

Refractive power (mean of the refractive indices for sodium light) weak = 1·585.

These numbers indicate that beryl does not possess the brilliancy belonging to minerals whose refractive power is strong; that its pleochroism (face colours) is not marked; and that a thin section viewed between crossed nicols will give colours of low orders as compared with minerals of strong birefringence.

Diopside (Fig. 344).—Birefringence positive, strong; axial plane (010).

	Red (Li).	Yellow (Na).	Green (Tl).
α	1·6675	1·6710	1·6749
β	1·6744	1·6780	1·6818
γ	1·6962	1·7000	1·7045
$\gamma - \alpha$	0·0287	0·0290	0·0296
$c : \gamma$	+ 39° 12′	+ 39° 6′	+ 39° 3′
2V	58° 52′	58° 43′	58° 30′

Absorption weak, α olive-green, β grass-green, γ grass-green.

The above numbers show that the refractive power β and the birefringence $(\gamma - \alpha)$ are strong. The acute bisectrix is inclined at about 39° to the vertical axis in the obtuse angle between a, c, and is the vibration direction corresponding to the index γ. The dispersion of the bisectrix is very

[1] Many authors use the symbols a, b, c to denote the absorption corresponding to α, β, γ respectively; with this notation the above character of cordierite would be expressed:— c (b) > b (a) > a (c).

slight, not more than 9′ between red and green light; the dispersion of the optic axes is $\rho > v$, but very slight, being only 22′ between red and green light.

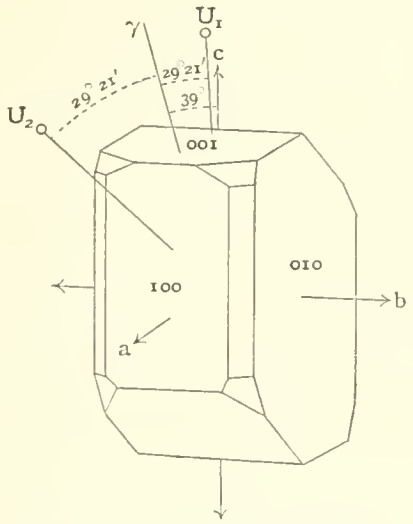


Fig. 344.—Optic Axes of Diopside.

The mineral possesses marked brilliancy and very slight pleochroism, and thin sections give interference tints of high orders as compared with beryl.

The positions of the optic axes U_1U_2 and of the acute bisectrix γ are given in Fig. 344.

CHAPTER VII

ON THE DETERMINATION OF OPTICAL PROPERTIES BY THE MICROSCOPE AND GONIOMETER

It now remains to show how the optical constants of a mineral are practically determined or estimated. Measurement of the three principal indices of refraction of a biaxial crystal by the ordinary methods would require two prisms cut symmetrically out of the crystal with their edges parallel to two axes of the indicatrix; each prism would then yield two refracted images of the collimator slit when examined by means of the goniometer of Fig. 265, and each image would suffice for the measurement of one index by the method of minimum deviation as described in all text-books of physics.

For the practical purposes of the mineralogist in the identification of a transparent mineral it is generally sufficient to measure the mean refractive power and the birefringence, and to find the position of the optic axes, and the sign of the birefringence. The dispersion of the optic axes or of the bisectrix can be sufficiently estimated by observation of the interference figure in white light.

1. **The Refractive Power and the Birefringence.**—The refractive power of a crystal may often be determined by employing two natural faces as a refracting prism, and using the goniometer to measure (1) α, the angle of the prism as defined on p. 31; (2) δ, the angle of least deviation of the light traversing the prism. The index of refraction μ is then given by the formula

$$\mu = \frac{\sin \frac{(180^\circ - \alpha) + \delta}{2}}{\sin \frac{180^\circ - \alpha}{2}}.$$

The crystal will in general yield two images of the collimator slit, which may be seen side by side in the field of the telescope, and from them two indices of refraction will be obtained; their mean may be taken to represent the refraction, and their difference the birefringence of the crystal in the direction of the transmitted light (*mn* in Fig. 345).

If the mineral be uniaxial and the faces be two faces belonging to

prism forms, these two indices will be actually ω and ϵ, and their difference will be the accurate measure of the birefringence of the mineral. For of the two rays refracted through such a prism, one vibrates along a horizontal and the other along the vertical line, since the rays themselves travel in the horizontal plane. Fig. 345 represents the refraction of light through the faces *mn* of a hexagonal prism belonging to a positive substance.

A prism cut in any other direction will give two indices, one of which is ω, while the other lies between ω and ϵ.

Among biaxial minerals only those belonging to the orthorhombic system are likely to yield natural prisms suitable for measuring both the refraction and the birefringence.

For example a prism of the positive orthorhombic mineral of Fig. 346 will, by virtue of its symmetry, transmit light which in the direction of least deviation is travelling along the axis β, and therefore vibrating

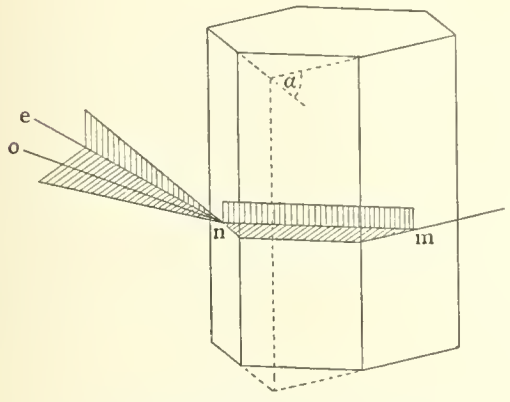


Fig. 345.—Refraction through Prism of Uniaxial Crystal.

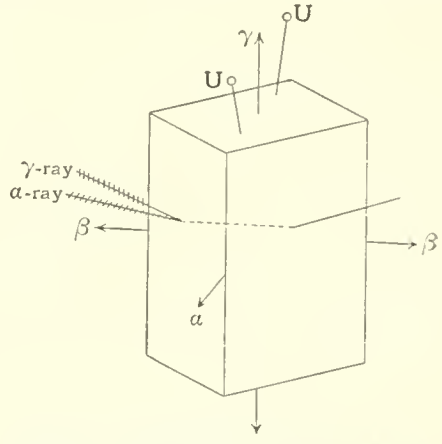


Fig. 346.—Refraction through Prism of Biaxial Crystal.

along the axes α and γ of the indicatrix: such a prism will therefore give the indices α and γ and the birefringence $\gamma - \alpha$. Unsymmetrical prism faces on crystals of the same mineral will give γ and an index between α and β, but their difference will be less than $\gamma - \alpha$, so that such faces will suffice to determine approximately the refractive power but not the exact birefringence of the mineral.

This is also the case in general with prisms formed by natural faces of monoclinic or anorthic minerals. With such crystals, if observations be made with several pairs of faces, those which give the widest difference between the two indices give, of course, a birefringence most nearly approaching the true birefringence $\gamma - \alpha$ of the mineral.

Both the refractive power and birefringence of facetted gem stones may very conveniently be measured in this way by utilising one pair of facets as a refracting prism.

For most minerals a prism of about 120° is convenient.

It should be remembered that a prism whose edge is parallel to one of the indicatrix axes, such as OC, will always give, as one of the two values, the corresponding index γ (as shown in Fig. 346). Thus one

principal index of a monoclinic crystal will be given by a prism whose edge is perpendicular to (010).

Total Reflection.—If the refractive indices of a mineral be below 1·75 they may be very conveniently measured by the method of total reflection. When light travelling in a glass whose refractive index is n meets the surface where it is in contact with a crystal whose refractive index μ is less than n, then, if the angle of incidence be equal to or greater than i where $\sin i = \frac{\mu}{n}$ the light is totally reflected. If, then, the index n of the glass be known and the angle i of total reflection can be measured, the index μ is ascertained.

The measurement can be thus made by the telescope goniometer of Fig. 265.

A prism ABD of highly refracting glass is mounted on the crystal

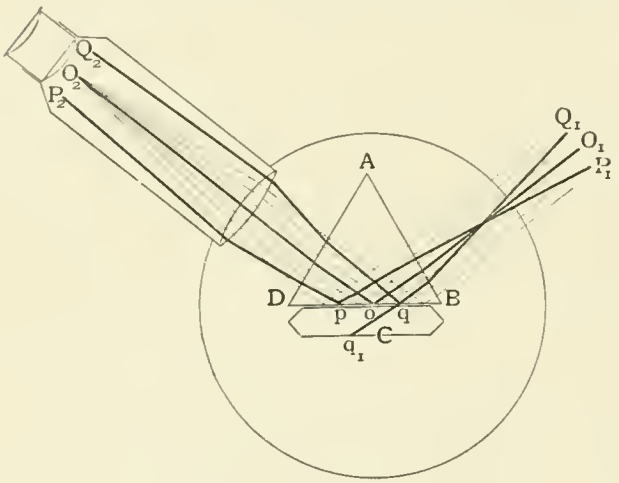


Fig. 347.

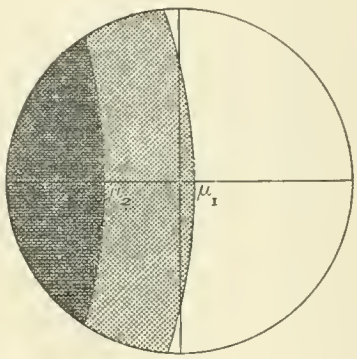


Fig. 348.

Figs. 347, 348.—Measurement of Indices by Total Reflection.

holder and adjusted (Fig. 347). The crystal C is fixed to an adjustable holder so that one of its faces is in true contact with the face BD of the prism, and perfect contact is assured by placing a drop of methylene iodide between C and BD. Light enters the prism through A, is reflected at the surface of C, and is observed through the telescope T. All the light (o to p) within the prism incident sufficiently obliquely upon C is totally reflected, and is therefore more brilliant than that (o to q) falling upon C with a smaller incidence, since some of the latter is lost by refraction into C.

The field of the telescope is consequently illuminated as in Fig. 348, where the brilliant right-hand portion is due to the light O_2P_2 which has been totally reflected. In an isotropic substance, such as a cubic crystal, this is divided from the darker left-hand side by a single sharp line corresponding to the angle of incidence which belongs to its index of refraction; in the case of other crystals the field is crossed by two lines corresponding to the two angles of incidence which belong to the two indices μ_1 and μ_2.

Evidently the angle of the glass prism and its refractive index being known, the angle of emergence of the light through B, and hence the angle i of total reflection may be easily measured. This gives for the particular face of the crystal C, which is in contact with BD, two indices of refraction, which can be calculated from the angle of the prism and its known refractive index; the greatest difference which can be obtained between the indices by turning each crystal face in its own plane, so as to be always in contact with BD, measures the birefringence.

The total reflectometer of Fig. 349 is a convenient instrument by which an approximate measurement of the refractive power and birefringence of any face of a crystal may be quickly and easily made.

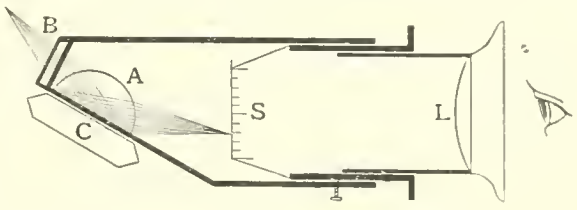


Fig. 349.—Total Reflectometer.

At one end of the tube represented in Fig. 349 is a hemispherical lens A of highly refractive glass with its centre in the axis of the tube and the plane surface inclined at about 30° to the axis. Diffused light falls upon this through a ground glass at B. S is a scale engraved upon glass, and L is a lens through which S is viewed. A plane face of the crystal C being pressed against the front of A after a drop of methylene iodide has been interposed between C and A, the light incident sufficiently obliquely through A suffers total reflection. A corresponding portion of the scale is more brilliantly illuminated than the remainder, and, as before, two shadows, D, E (Fig. 350), are seen across the field of view; these correspond to two refractive indices of the crystal face. It is only necessary to calibrate the scale beforehand by placing different isotropic substances, liquid or solid, of known refractive index against A; these should be viewed by sodium light and the corresponding points of the scale which are intersected by the shadow are to be noted for each. The refractive indices corresponding to a number of readings on the scale are thus ascertained, and the value of the remainder can be found by constructing a curve. F represents the shadow given by an isotropic substance whose refractive index is less than those corresponding to D, E.

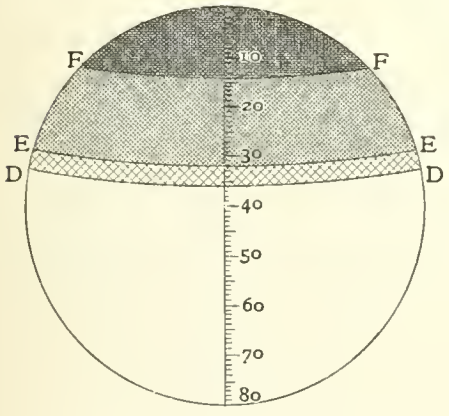


Fig. 350.—Field of Reflectometer.

The film of liquid, being a plate, does not alter the angle registered by either instrument; and its refractive index need not be known.

Other liquids of higher refractive index might be employed, but they are for the most part corrosive or unstable. One of the most convenient of all liquids is α-monobromo-naphthalene, whose index is 1.66,

and therefore considerably less than that of methylene iodide, but it does not darken on exposure to light so readily as the latter.

The interval between the shadows D, E, indicates at a glance the magnitude of the birefringence, and when white light is used the breadth of the coloured fringe which borders each shadow indicates the dispersive power of the crystal.

2. **The Sign of the Birefringence.**—The sign of a mineral fragment, section, or crystal is ascertained by superposing upon it a slice of some crystal whose birefringence is known, and observing in what positions the latter increases or diminishes the effect of the crystal.

This can be done either in parallel light by observing the change in tint of the crystal itself, or in convergent light by observing the change in form of the interference figure.

We will consider the latter method first. The test-crystals used with convergent light are: (1) for uniaxial crystals a "quarter wave-length mica plate"; and (2) for biaxial crystals a "quartz wedge."

3. **Use of the Mica Plate with Uniaxial Crystals.**—Mica is a biaxial mineral (monoclinic) which very readily cleaves nearly perpendicular to the acute bisectrix; the cleavage flakes may be obtained of any thinness required. A cleavage plate by which the two waves of light travelling in the direction of the acute bisectrix are made to differ in phase by a quarter wave-length of light of mean colour is called a quarter wave-length plate; viewed by convergent light it will itself give an interference figure, in which the first ring is continuous and like the second ring of Fig. 351.

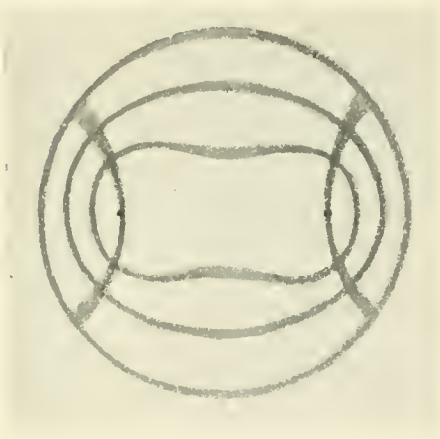


Fig. 351.—Difference of Phase $< \lambda$.

The plate is cut into an oblong form (Fig. 352), and mounted for protection between two slips of glass; its greatest length is that of the plane containing the optic axes. Mica is a negative mineral, so that of the two extinction lines in the plate, one, OB, is the mean axis of the indicatrix proportional to the index β of the mica, and the other, OC (the obtuse bisectrix), is the greatest axis, proportional to the index γ. Fig. 352 shows the nature of the elliptic section of the indicatrix by the mica plate. A ray entering the plate is divided into two, one vibrating along OB and travelling faster, the other vibrating along OC and travelling more slowly; and in their passage through the plate the latter is retarded by $\frac{1}{4}\lambda$ behind the former. Consider the action upon a uniaxial figure of

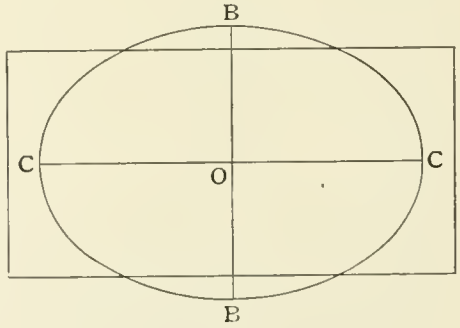


Fig. 352.—Birefringence of Mica Plate.

such a plate inserted in the microscope tube between the section and the analyser. Let Fig. 353 represent the interference figure of a positive uniaxial mineral, and let the mica plate be inserted along the line CO at 45° to the lines OP, OA.

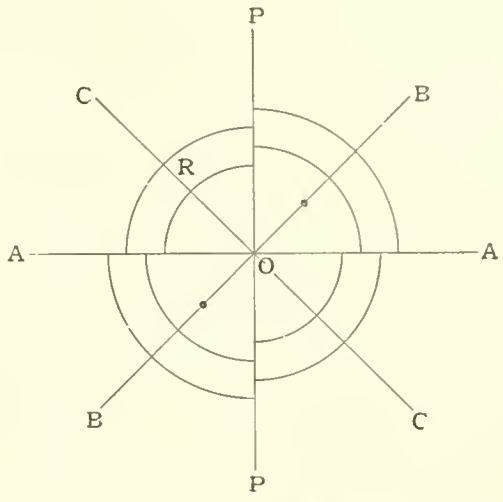


Fig. 353.—Action of Mica Plate.

Consider any point R of the first ring, where the difference of phase is λ; it is due to the interference of two rays, one, the extraordinary, vibrating along RO, which is parallel to OC; the other, the ordinary, vibrating parallel to OB (Fig. 321). Since the crystal is positive the latter is the minor axis of the indicatrix belonging to the crystal, and therefore the ray vibrating in that direction corresponds to a lesser refractive index and travels more rapidly than the other, both in the crystal section and in the mica plate. The difference of phase will be $\lambda + \frac{1}{4}\lambda$ instead of λ, and there will be light instead of darkness at the point R. The first dark ring will be produced at a point between R and O, where the difference of phase due to the crystal was $\frac{3}{4}\lambda$, so that it is increased by the action of the mica plate to λ, and complete interference takes place.

The effect of the mica plate in the whole of the two quadrants

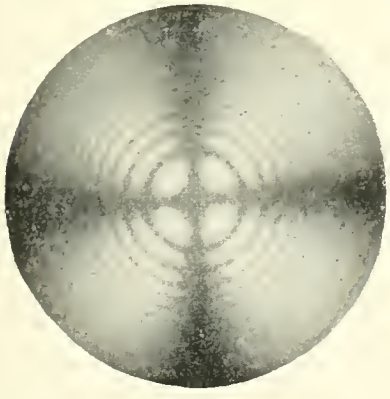


Fig. 354.—Uniaxial Figure.

Fig. 355.—Uniaxial Figure (Mica Plate inserted).

bisected by CC will be the same: the rings will all be shifted inwards towards the centre; in these quadrants the effect of the mica is added to the effect of the crystal. The result is the same as though the crystal section were increased in thickness, and the rings are drawn closer together.

In the remaining two quadrants the effect is just the contrary. Here again the extraordinary ray vibrates in the plane containing the ray and

the optic axis; but this plane is now parallel to the line OB in the mica plate, and it is, therefore, the greater radius in the indicatrix of the mica, but the minor axis of the indicatrix belonging to the crystal. In these quadrants, therefore, the action of the mica plate is opposed to that of the crystal; the result is the same as though the section were made thinner, and the diameters of the rings are increased. At two points in these quadrants, where the difference of phase due to the crystal is $\frac{1}{4}\lambda$, the double refraction of the crystal is exactly annulled by that of the mica, and in each of these quadrants there will be a dark spot, while the centre of the field becomes light.

For a positive crystal, then, the rings expand along the shorter diameter of the mica plate and contract along the longer diameter. In a negative crystal the vibration directions corresponding to greatest and least velocity are interchanged, and the same considerations will show that the rings must expand along the length of the mica plate and contract along its breadth.

The action of the mica plate on the uniaxial interference figure of Fig. 354 is shown in Fig. 355.

As a *memoria technica* it may be observed that the line along which the optic axis opens out into two dark spots forms a *plus* sign with the length of the mica plate in a positive crystal, and a *minus* sign in a negative one.

The mica plate cannot be conveniently used with extremely thin sections in which the rings are very widely separated.

4. **Use of the Quartz Wedge with Biaxial Crystals.**—The principle of noticing in what positions a crystal of known sign increases the double refraction of a section, and in what positions it diminishes the double refraction, when placed over the section, is also utilised in determining the sign of biaxial crystals. But here the mica plate cannot be so conveniently used, since there is no point like the centre of the uniaxial figure through which the vibration direction of one of the rays always passes.

Quartz is a positive mineral. A section cut from a long prism of quartz parallel to the optic axis is therefore one in which the length of the section is the vibration line corresponding to rays of least velocity or greatest refractive index; in this respect it resembles the mica plate. A section cut parallel to the optic axis so as to be thinner at one end than the other (Fig. 356, side view) will, when examined between crossed

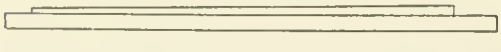


Fig. 356.—Quartz Wedge on a Glass Slip, Side View.

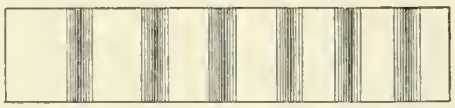


Fig. 357.—Quartz Wedge viewed in Parallel Light.

nicols in parallel light, exhibit tints which vary with the thickness of the section; at the thinner end it may show the faint grays and yellows of the first order of Newton's scale; and these rise gradually through the second and third orders as the wedge is examined successively farther

and farther from its thinnest part; bands of one colour after another will appear in succession as the wedge is moved across the stage (Fig. 357, with which compare Fig. 284, on p. 124). Such a wedge affords the means of superposing any desired thickness of quartz upon the section which is being examined.

The quartz wedge should be as thin as possible at its edge and increase very gradually towards its thicker end. In the examination of biaxial interference figures it is (like the mica plate) inserted through an aperture in the tube between the objective and the analyser, so that its length, the line of the optic axis, is inclined at 45° to the planes of polarisation and analysation.

Let Fig. 358 represent the interference figure seen along the acute bisectrix of a *negative* biaxial crystal in the diagonal position, and let the quartz wedge be first inserted parallel to the plane of the axes. In the crystal, OB is the mean axis, OC the greater axis of the indicatrix; in the indicatrix of the quartz wedge also OB is the minor axis, and OC the major axis. Hence at the centre of the figure the effect of the quartz wedge will be added to that of the crystal section. The result will be the same as though the section were increased in thickness; complete interference will take place with rays of less obliquity than for a thin section; and the coloured lemniscates, if visible, will be drawn closer together.

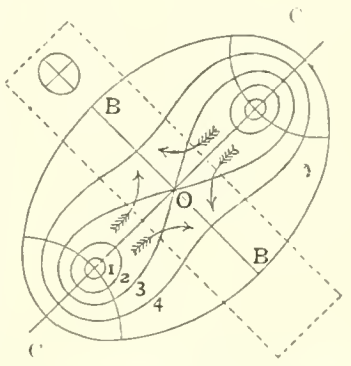


Fig. 358.—Action of Quartz Wedge on Biaxial Figure.

Let the quartz wedge be now inserted, as in Fig. 358, perpendicular to the line joining the optic axes of the crystal. The directions corresponding to greatest and least indices in the wedge are now reversed, and its effect, acting in opposition to that of the crystal, produces the same result as though the section were made thinner. The rings at the centre of the figure broaden out, and as the wedge is pushed farther and farther across the field of view, so that the thickness of quartz continually increases, each pair of rings which surround the axes will be seen to expand. The pair of rings 1 pass successively into the form of 2, 3, and 4; they meet in the centre as a figure of eight and grow outwards as a continuous lemniscate in a direction at right angles to the line of the axes, as shown by the arrows. If, on account of the thickness of the section, no rings are visible, a sufficient thickness of the quartz wedge will cause them to appear in the centre of the field of view.

On the other hand, in a *positive* biaxial crystal the obtuse bisectrix, the extinction line in the plane of the optic axes, is the least axis of its indicatrix, and the rings will expand when the quartz wedge is inserted parallel to the optic axes.

Hence in a negative crystal the rings, if visible, expand outwards (or, if not visible, begin to make their appearance) when the quartz wedge is inserted perpendicular to the plane of the optic axes; in a

positive crystal, when it is inserted parallel to the plane of the optic axes.

It is well always to examine the section by inserting the wedge first in one of these directions and then in the other, and observing whether the rings expand outwards in one position of the wedge, and *also* contract inwards in the other. Otherwise it is possible to be misled by a contraction of the rings, which may appear to be due to the quartz wedge adding its effect to that of the section, whereas, in reality, the two are opposed to one another. For if the section be very thin, the quartz wedge may at its first insertion have the effect of widening the rings; a moment may then arrive at which the double refraction of the section and the wedge are the same but opposite, so that they exactly counteract each other's effect; then an increasing thickness of quartz may cause the rings to reappear, and to continually contract, not because the effect of the quartz is continually added to that of the section, but because it is continually preponderating more and more over the section, although they are acting to produce opposite effects. There is no chance of such a mistake if the quartz wedge is afterwards inserted in the other direction. In the above observations no attention should be paid to the changes which are seen in the rings towards the edge of the field of view.

When the quartz wedge is not thin enough, it is advisable to use a quartz plate cut perpendicular to the axis. If such a plate be inserted in the microscope tube and slightly tilted by rotation about OB, its optic axis (the major axis of its indicatrix) will lie in the plane OC; but the double refraction will be very slight, since the observer is looking very nearly along the optic axis, and the effect will be the same as that of inserting an extremely thin wedge along OC. A slight rotation of the plate about OC will be equivalent to inserting a very thin wedge along OB.

5. **The Method of Compensation.**—By the use of the wedge it is therefore possible, from the interference figure viewed along a bisectrix, to determine which of its two extinction lines is the major axis of the ellipse in which the section cuts the indicatrix, *i.e.* is the vibration direction of the slower ray; from this it is known whether the bisectrix (either the acute or obtuse bisectrix) is positive or negative. If the section be cut parallel to the optic axes of a biaxial crystal, or parallel to the optic axis of a uniaxial crystal, no interference figure will be seen; but it is still possible to determine the sign of the crystal if we can find which of the extinction lines in the plane of the section is the greater and which the lesser radius of the indicatrix. Or, more generally still, it is possible in *any* section cut from any birefringent crystal to determine which of the two extinction lines is the vibration line for greater index by using the quartz wedge or some similar contrivance—not in convergent but in parallel light.

Thus, let the figure (359) represent any crystal section placed in the diagonal position, *i.e.* at 45° to its position of extinction, and of the two extinction lines let OC be the greater radius, and OB the lesser radius

of the indicatrix, so that the section of the indicatrix is the ellipse shown in the centre of the figure.

If now the quartz wedge (whose corresponding ellipse is shown at the thicker end) be inserted along the line OB it will act in opposition to the section; the double refraction will be continually diminished—the tints of the section will fall in the Newton scale until finally the section will appear of a dull gray, when the wedge exactly "compensates" the crystal, so that the double refraction is almost destroyed. An increasing thickness of quartz will then cause the tints to reappear and to rise through the scale of colours. Whenever compensation can be effected, or the colours be made to descend in the scale, the wedge is acting in opposition to the section. If, for example, a thin prism of a uniaxial mineral is compensated by the insertion of the quartz wedge parallel to its length, it is known to be negative, since it must be opposite in sign to the quartz. Whatever the thickness or double refraction of the section, a suitable thickness of quartz or of some other mineral of known sign can be found which will produce compensation in one position or the other. If the section is very thin, a thin section of quartz cut perpendicular to its axis may be used as recommended above, the double refraction being induced by a very slight tilting of the quartz in one direction.

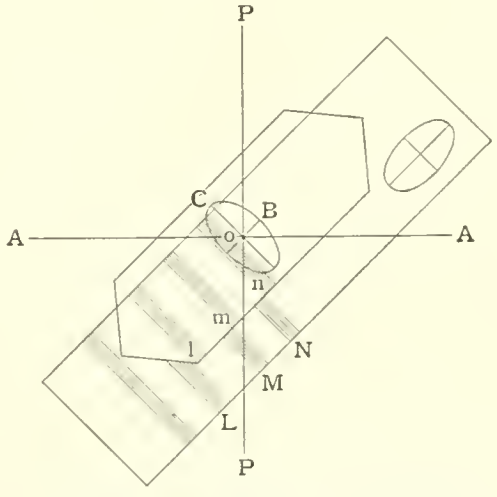


Fig. 359.—Compensation by Quartz Wedge.

An easy way of determining whether the birefringence of the quartz wedge is increasing or diminishing the action of the crystal is to observe the displacements of the fringes where the wedge overlaps the crystal. Thus in Fig. 359 the wedge is so arranged as partly to overlap the crystal; the second fringe as seen in the quartz is at M; but since the birefringence of the crystal is opposed to that of the quartz, the light, in order to produce the same effect, must traverse a greater thickness of quartz where it overlaps the crystal, M is displaced to *m* and all the fringes are displaced towards the thick end of the wedge (*m*, *n*, etc.).

If the quartz and the crystal are co-operating the displacement is towards the thin end of the wedge.

6. **The Method of Sensitive Plates.**—As suggested by this last experiment, the change of tint produced, not in the crystal, but in the compensator itself, may be utilised to determine the sign of the birefringence. For this purpose the compensator is a very thin section of some known mineral; for instance, a cleavage lamina of gypsum cleaved so thin as to give the red of the first order as its interference colour. When the crystal section adds its effect to that of the gypsum, the slightest change makes itself apparent in a rise of the colour to blue

or yellow of the second order; when the crystal section acts in opposition to the gypsum, the tint falls to the faint yellow or gray of the first order.

Such a plate is extremely sensitive, and may be used in examining minerals whose double refraction is very weak; such, for example, as give only the gray of the first order. The positions of the extinction lines in the gypsum and their relative magnitudes as radii of its indicatrix being known, a rise in the tint indicates that they are superposed to corresponding extinction lines in the crystal; a fall in tint indicates that the vibration direction corresponding to the larger refractive index in the gypsum coincides with that belonging to the less refractive index in the crystal.

7. **Determination of the Pleochroism.**—It was shown above (p. 160) how the dichroscope is used to place the two axial colours belonging to any crystal section side by side, so that they may be distinguished.

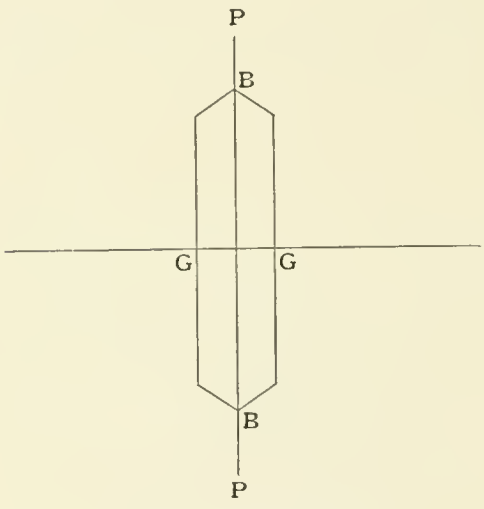


Fig. 360.—Pleochroism.

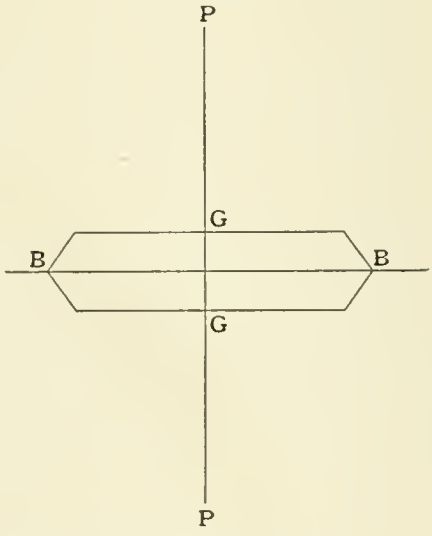


Fig. 361.—Pleochroism.

With the polarising microscope they may be viewed *successively* and determined upon even minute fragments. Let Fig. 360 represent a pleochroic crystal (such as andalusite) lying on the microscope stage. Let BB and GG be its two extinction lines, so that the vibrations of the light traversing the crystal take place along BB and GG. Let the former be brown in colour, and the latter green.

Then in the position of Fig. 360 the plane-polarised light enters the crystal, vibrating along BB; it traverses the crystal unaltered as plane-polarised light, and the section appears of a brown tinge.

Now let the stage be turned through 90°, so that the section lies as in Fig. 361. The rays transmitted by the polariser now traverse the crystal, vibrating along the direction GG, and the crystal appears of a green tint.

Hence a pleochroic crystal will change colour as the stage is rotated over the polariser; a crystal of coloured hornblende, tourmaline, or mica

(viewed along the cleavage) will show this property in a very conspicuous manner.

In tourmaline the ordinary ray is almost entirely absorbed; a thin prism of this mineral which appears fairly transparent and only faintly coloured in the position of Fig. 360, becomes dark brown and almost opaque when in the position of Fig. 361, in which its optic axis BB is parallel to the longer diagonal of the polarising nicol.

A crystal of mica viewed parallel to its cleavage, *i.e.* across and not along the hexagonal prism, appears dark when its cleavage lines are parallel to PP (Fig. 362), since the light, whose vibration direction is in the cleavage plane, is more absorbed than the light polarised in that plane and vibrating perpendicular thereto.

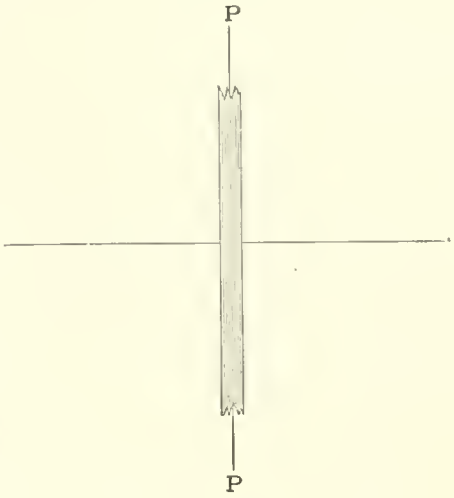


Fig. 362.—Mica in Position of Maximum Absorption.

8. **Measurement of the Optic Axial Angle.**—To measure 2E, the apparent optic axial angle in air of a biaxial crystal, a plate must be obtained which is perpendicular to the acute bisectrix, and the position of the optic axial plane must be ascertained by a preliminary observation of the plate in convergent light. The experiment is most easily made with a plate of topaz, which cleaves readily perpendicular to the acute bisectrix.

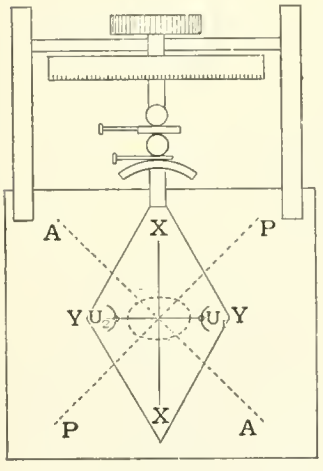


Fig. 363.—Stage Goniometer.

The optic axes are seen to lie in the plane of the shorter diagonal of the basal cleavage. The plate is then mounted on a "stage goniometer" shown diagrammatically in Fig. 363.

This is merely a small goniometer with the ordinary centreing and adjusting movements of Fig. 262, p. 101, which can be screwed to the stage of the microscope.

It is advisable that the microscope should be of the "Dick" pattern, in which the stage is fixed and the nicols rotate together (Fig. 364).

The crystal plate is to be carefully mounted and adjusted so that the axial plane U_1U_2 is perpendicular to the goniometer axis (Fig. 363); the polariser and analyser are set so that their principal planes PP, AA are at 45° to the cross-wires of the eye-piece; the cross-wires XX, YY themselves being parallel and perpendicular to the goniometer axis.

By means of a screw shown below the stage (Fig. 364) the goniometer is raised so far that the plate can be turned round without coming in contact with the stage, and the microscope tube is racked up so far that the plate does not come into contact with the objective. This renders it

impossible to see more than a small area of the interference figure quite near the centre of the field of view, but for purposes of measurement that is all that is required. For when the goniometer circle is turned in one direction the figure moves across the field of view until one optic axis approaches the centre of the field, and by turning the circle in the other direction the other optic axis can be brought into the centre of the field.

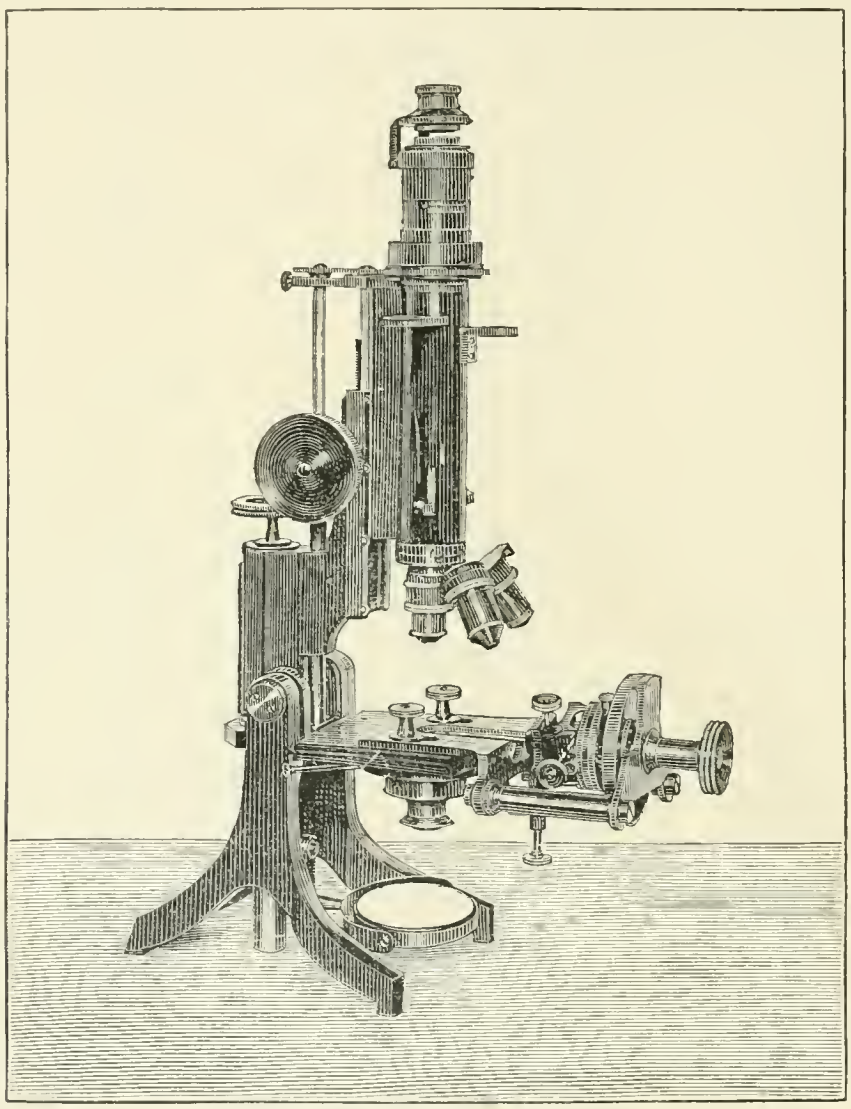


Fig. 364.—Microscope with Stage Goniometer.

The plate is adjusted by means of the goniometer, so that as it is rotated, first one and then the other optic axis passes exactly along the horizontal cross-wire of the polariscope. The adjustments are made just as in measuring a crystal on the goniometer.

Each optic axis is the central point of the apex of one of the hyperbolic arms belonging to the biaxial figure; in order to ascertain when this point coincides with the centre of the field of view the goniometer circle is moved until first the convex side and then the concave side of

the hyperbola is brought into contact with the vertical cross-wire. The two corresponding readings are noted and their arithmetic mean is taken as the reading for one optic axis; a similar reading is obtained for the other optic axis, and the difference between the two readings is the angle 2E. The disc is then turned until the plate is reversed; the measurement is repeated from the other side, and thus a second determination is made of the same angle.

From the apparent axial angle 2E the true axial angle 2V can be deduced (if the mean index of refraction β is known) by means of the relation $\sin E = \beta \sin V$ (see p. 153).

Measurement of 2V.—It is possible, by using a second plate cut perpendicular to the obtuse bisectrix, to determine 2V without knowing anything of the indices of refraction.

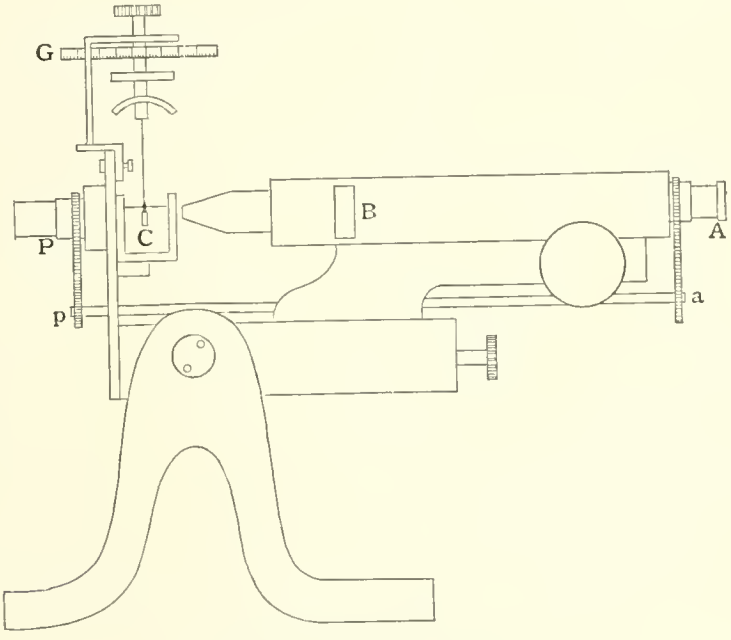


Fig. 365.—Measurement of 2V.

It is not possible to measure the apparent obtuse angle in air $2E_o$ by this plate, for if the apparent acute angle $2E_a$ is small, then $2V_o$ is so large that rays travelling in the crystal along the optic axes experience total reflection within the second plate.

When, however, the section is immersed in oil, or some other liquid of which the refractive power is nearly equal to that of the crystal, total reflection no longer takes place; it is generally easy to obtain a measurement even for the obtuse angle, and, further, by measuring both the acute and the obtuse angle in the same oil the true angle 2V can be found without even a knowledge of the refractive index of the oil.

For this purpose a small glass trough with parallel sides is filled with oil and inserted between the condenser and the objective, the microscope tube having been first placed in a horizontal position. The trough is inserted from below, so that the crystal section C is completely immersed in the oil, and the section is to be so small that it may be rotated in the

trough without coming into contact with the sides. No deviation of the ray is produced by refraction from the oil into air, for the trough is enclosed by a pair of truly parallel plates, and is placed with its sides perpendicular to the axis of the microscope. In Fig. 365 P and A are polariser and analyser which rotate together by means of the rod *ap* and toothed wheels at *a* and *p*. B is the "Bertrand" lens, which renders the interference figure visible; G is the goniometer disc.

With this apparatus a measurement can be obtained from the first plate of the apparent acute axial angle in oil, $2H_a$; and from the second plate the apparent obtuse angle in oil, $2H_o$, can be determined in the same way.

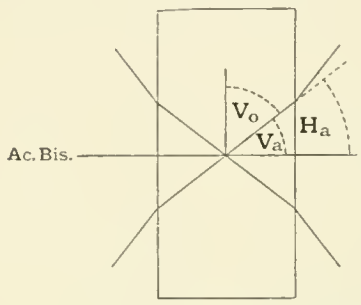


Fig. 366.

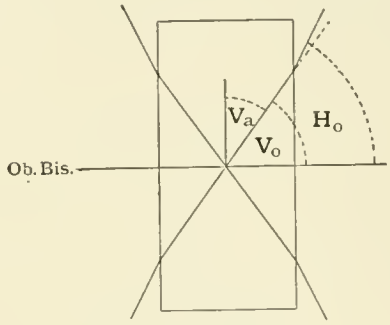


Fig. 367.

Thus if μ be the mean index of refraction of the crystal into the oil, *i.e.*

$$\mu = \frac{\text{mean index of the crystal}}{\text{index of the oil}}$$

in the first determination (Fig. 366),

$$\frac{\sin V_a}{\sin H_a} = \mu$$

in the second determination (Fig. 367),

$$\frac{\sin V_o}{\sin H_o} = \mu,$$

$$\therefore \frac{\sin H_a}{\sin H_o} = \frac{\sin V_a}{\sin V_o} = \tan V_a,$$

$$\text{since } V_o = 90 - V_a.$$

Thus from the two observed angles H_a and H_o the true axial angle V_a is completely determined without any knowledge of μ, as

$$\tan V_a = \frac{\sin H_a}{\sin H_o}.$$

Calculation of 2V.—If the three principal refractive indices have been measured on the goniometer as described above, the value found by observation for the optic axial angle may be confirmed by calculation from the indices.

From the geometry of an ellipsoid it may be proved that if OA, OB, OC be its semi-axes, then the angle V between OC and the perpendicular to one of its circular sections is such that

$$\tan V = \frac{OC}{OA}\sqrt{\frac{OA^2 - OB^2}{OB^2 - OC^2}}.$$

But α, β, γ, are the semi-axes of the indicatrix, and the primary optic axes are perpendicular to its circular sections.

Hence :—

$$\tan V = \frac{\gamma}{\alpha}\sqrt{\frac{\alpha^2 - \beta^2}{\beta^2 - \gamma^2}}.$$

In order to identify a mineral the apparent angle 2E is generally sufficient without the necessity of measuring the refractive indices and the true angle 2V.

In any case the first process in the case of any crystal is to find the position of the optic axis or axes by trial. This is to be done by examining the crystal in convergent light through parallel pairs of faces or cleavage plates until some portion of the interference figure can be seen, sufficient to indicate the position of the optic axis or the acute bisectrix.

There is, of course, some difficulty in finding the positions of the optic axes by trial in a crystal, or an angular fragment, or a cut gem, because if an axis emerges very obliquely or near a corner it may be refracted out at such an angle as to lie outside the field of view. This difficulty is obviated by immersing the crystal in an oil, or other liquid of high refractive index, contained in a cell or trough between the condenser and the objective ; the rays then emerge from the crystal into a medium of nearly the same refractive index, and are only very slightly refracted, and the interference figure is seen almost as clearly as through a plane section. If the crystal be sufficiently small it may even be immersed in a drop of oil contained between the objective and the condenser. Thus, for example, if the minute pointed summit of a pyramidal crystal of apophyllite, such as those from Mexico, be cleaved off and be placed on its cleavage surface in a drop of cassia oil on a thin glass slip on the microscope stage, so that the fragment is entirely immersed ; then when the objective is lowered until it is in contact with the oil (not with the crystal), a perfect uniaxial interference figure will be seen just as clear as that shown by a cleavage plate of the mineral, although the crystal is viewed directly through the acute apex.

CHAPTER VIII

THE OPTICAL PROPERTIES OF TWINNED AND PSEUDO-SYMMETRIC CRYSTALS

It was mentioned above that crystals belonging to any system may in their angles approximate very closely to the symmetry of a more symmetrical system; when this is the case the resemblance is generally made still more close by mimetic twinning; thus in an orthorhombic mineral like aragonite (or witherite), which has a prism angle nearly equal to 60°, the vertical axis is *nearly* an axis of trigonal symmetry, and thus may be called an axis of pseudo-symmetry.

When three crystals of aragonite are twinned about the prism faces and interpenetrate, the resemblance to a hexagonal prism is still more complete. Each crystal may be regarded as derived from the next by a rotation of about 60° round the axis of pseudo-symmetry, and consequently that axis has become *very nearly* a real axis of trigonal symmetry in the compound crystal. The outlines of the three component crystals are easily distinguishable by cutting a section across the prism parallel to their common basal plane, and examining it in polarised light between crossed nicols; each individual of which the hexagonal plate is composed will then "extinguish" uniformly within itself, but not at the same time with its neighbours. Fig. 368 represents a triple crystal of aragonite in which the individuals I and II are twinned together on the prism face m_2; I and III are twinned together on the face m_3. The striations on each individual represent the direction of its brachypinakoid (010). Each of the three individuals is in its position of extinction when these striations are parallel to a cross-wire of the microscope.

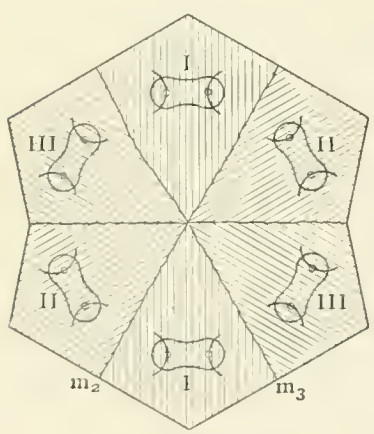


Fig. 368.—Aragonite.

When two plates of crystal overlap, all that was said above concerning the transmission of light through a single crystal no longer holds good, and there is in general no position in which the compound crystal appears dark between crossed nicols. Only when the extinction lines of the

two plates happen to coincide is there any definite position of extinction. Hence if there be an area where two or three crystals overlap near the centre of Fig. 368, this will always transmit light as the stage of the microscope is rotated.

Examined in convergent light each of the three individuals will give a biaxial interference figure in which the plane of the optic axes is parallel to the macro-pinakoid, *i.e.* is perpendicular to the striations of Fig. 368. Only in the area where two or more individuals overlap there will be indications of two or three pairs of optic axes visible simultaneously, and the coloured fringes surrounding them will be no longer the regular curves of Fig. 322.

It sometimes even happens that the overlapping of a number of biaxial plates whose acute bisectrices coincide gives rise to an interference figure closely resembling and scarcely to be distinguished from a uniaxial figure. As was shown by Nörremberg, this effect of overlapping may be studied by superposing cleavage plates of mica upon each other. If a sufficient number of sufficiently thin plates be piled with their axial planes at right angles to each other, the combination will give an apparently uniaxial interference figure in convergent light.

When a pseudo-symmetric crystal is composed of completely interpenetrant crystals it may be impossible to find any portion which either possesses a definite position of extinction, or yields a definite interference figure. But in general a thin section of a pseudo-symmetric crystal, when examined by the polarising microscope, will appear to be divided into regular and differently orientated sectors, as in Fig. 368. Now, it was stated above that crystals belonging to the cubic system are not doubly refracting. It has, however, long been observed that many apparently cubic minerals transmit light between crossed nicols—some in irregular patches, and some in geometrical sectors. For example, a section of the white garnet from Auerbach, cut parallel to (111), shows a regular division into three doubly refracting areas, a section parallel to (100) shows four such areas, while sections parallel to (110) extinguish uniformly.

Such peculiarities were generally supposed to be due to internal strains set up during crystallisation as a result of cooling, and to be similar to the double refraction of chilled or compressed glass; they have been imitated by gelatine models of various crystalline forms which have been cut while moist, so that in the contraction of drying they have been symmetrically strained. They were known as "optical anomalies." In 1876, however, it was shown by Mallard that in general these appearances are to be explained as the result of mimetic twinning in pseudo-symmetric crystals. An extremely instructive case is that of leucite. This mineral occurs almost invariably in icositetrahedra $\{211\}$, which are so characteristic of the mineral that this form is often known by the name of the leucitohedron. It was, however, observed that the crystals are traversed by twin lamellæ parallel to four faces (D, E) of the dodecahedron; in Fig. 369 these are (011), (01$\bar{1}$), (101), (10$\bar{1}$). Now, if the dodecahedron is a plane of symmetry it cannot also be a twin plane;

the crystals cannot, therefore, belong to the cubic system. Accurate measurements made by vom Rath then showed that the angles are not those of the icositetrahedron {211}, whose faces should be inclined at 48° 11½′; for in leucite the terminal faces *o* are inclined to each other at 49° 57′, and the lateral faces *i* at 48° 37′; the mineral was therefore regarded as tetragonal, consisting of two forms—the tetragonal bipyramid *o* {112}, and the ditetragonal bipyramid *i* {211}—twinned on faces of the tetragonal bipyramid {101} such as *eaf* (Fig. 369).

If this be the case, the mineral, as tetragonal, should be uniaxial. The observations of Mallard and others, however, have shown that, although in parts apparently uniaxial (owing to the appropriate overlapping of biaxial plates), the crystals are elsewhere biaxial, and therefore cannot possess a symmetry higher than that of the orthorhombic system. In accordance with this it is found that there are in reality also twin lamellæ parallel to the remaining dodecahedron faces (110), (1$\bar{1}$0) at F; the crystal must therefore be regarded as orthorhombic but referable to three *nearly* equal rectangular axes. The two lateral axes are so nearly equal that angular measurements alone are not sufficient to disprove the apparently tetragonal symmetry.

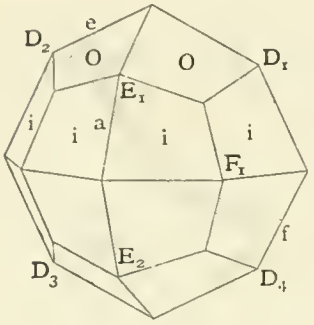


Fig. 369.—Leucite.

In leucite the crystals are traversed by so numerous and such fine twin lamellæ that it is difficult to obtain at any point in convergent light the biaxial figure of a single homogeneous crystal.

Fig. 370 represents a section of leucite cut parallel to (001) viewed between crossed nicols. The broad bands denote the twin lamellæ parallel to the four pairs of dodecahedron faces which are inclined to the section, and the fine bands those parallel to the two pairs of dodecahedron faces (110), (1$\bar{1}$0) which are perpendicular to the section. Fig. 371 is a section cut parallel to (111) and exhibits the same twin lamellation.

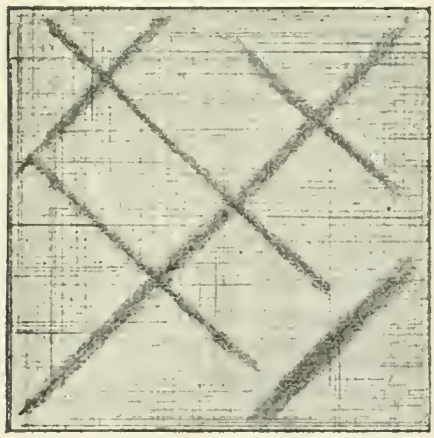


Fig. 370.—Leucite, (001) Section.

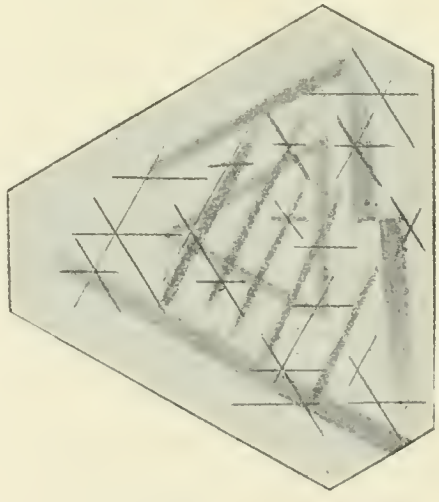


Fig. 371.—Leucite, (111) Section.

Boracite, again, is apparently cubic and tetrahedral in symmetry; but thin sections parallel to the three cube faces show that the mineral is really biaxial; each such section is perpendicular to an optic axis of each of four component biaxial crystals. When viewed through a homogeneous patch which is not traversed by twin structures, boracite gives the biaxial interference figure of a mineral having an axial angle of about 90°. A boracite crystal is therefore composed of six or twelve pseudo-cubic "sub-individuals" which interpenetrate each other more or less completely and have their acute bisectrices perpendicular to the dodecahedron faces. The structure is similar to that of Fig. 253.

Now, one of the most singular facts concerning these and some other pseudo-cubic crystals is, that at a certain temperature they lose their double refraction and become isotropic; that is to say, belong really to the cubic system. Leucite becomes isotropic at a temperature near 433°; boracite becomes isotropic at a temperature of 265°; each crystal on cooling regains its original pseudo-symmetric character, although in boracite the boundaries of the various individuals usually change their original positions.

It was consequently supposed by some authors that leucite originally crystallised as a cubic crystal in the volcanic lavas in which it is found, and that its orthorhombic character is secondary and due to a transformation on cooling. According to this view the boracite substance is also capable of crystallising in two systems; the cubic variety is formed above 265° in a cubic form; on cooling it will be transformed into the other, the pseudo-cubic but biaxial modification. Further investigation has shown that in reality the majority of apparently cubic minerals must be regarded as pseudo-symmetric, and it is quite possible that in most cases, being pseudo-cubic, they have *originally* grouped themselves by twinning into mimetic crystals. Conspicuous examples, in addition to leucite and boracite, are analcite and some of the garnets. The only common cubic minerals in which the so-called optical anomalies are not usually apparent are spinel and cuprite.

Pseudo-symmetry is also to be found among minerals belonging to other systems; for example, the tetragonal apophyllite and idocrase—both of which generally consist of biaxial material, although some specimens give a uniaxial interference figure—and the hexagonal apatite and pyromorphite.

In the remaining systems these features are more difficult of proof, since it is far more difficult to distinguish between the biaxial interference figures of an orthorhombic and a monoclinic crystal than between a biaxial and uniaxial figure

In leucite, as we have seen, the pseudo-symmetry is betrayed by the external form; each face is not a plane reflecting surface, but is broken up into portions which belong some to one crystal and some to another.

This is an instance of those cases mentioned on p. 97, in which facets resembling vicinal faces are due to pseudo-symmetric twinning.

It is worthy of remark that when leucite is raised to a sufficiently high temperature, not only does it lose its double refraction, but all the

striæ and minute facets which accompany the twinning disappear at the same time and the faces of the icositetrahedron become smooth and plane. The indications of twin-structure reappear together with the double refraction when the crystal cools.

Airy's Spirals.—A very remarkable case of the overlapping of crystals is that of quartz, or any other uniaxial crystals which rotate the plane of polarisation. If a basal section of left-handed quartz be laid upon a basal section of equal thickness of right-handed quartz, the interference figure produced by the compound plate consists no longer of circular rings but of right-handed spirals. If the plates be interchanged so that the transmitted light enters the left-handed crystal first, the figure will be similar but left-handed spirals. These figures, which are known from the name of their discoverer as Airy's spirals, are often to be seen in a basal section of a quartz crystal, indicating that the crystal is really a twin of right- and left-handed individuals. It was shown by Reusch that the rotatory polarisation of quartz may itself be imitated by a pile of mica plates arranged like the steps of a spiral staircase, so that the axial plane of each is inclined at 120° to that below it. Such a "Reusch combination" rotates the plane of polarisation and gives an interference figure like that of quartz, Fig. 343.

BOOK II

THE GENERAL PROPERTIES

CHAPTER I

THE GENERAL PHYSICAL PROPERTIES

1. **Specific Gravity.**—By the *density* of a mineral expressed in any units is meant the mass of unit volume; *i.e.* in the metric system the weight in grams of 1 c.c. of the mineral.

The relative density of a mineral with regard to water, or the ratio of its density to that of distilled water at 4° C. is the *specific gravity*; this is measured by comparing the weight of any volume of the mineral with the weight of an equal volume of distilled water at 4°; the ratio of the former to the latter is the specific gravity of the mineral. If, for instance, a fragment of a mineral weighs half as much as an equal volume of water at 4° the specific gravity is 0·5; if it weighs exactly as much as an equal volume of water at 4° the specific gravity is 1·0; if twice as much the specific gravity is 2·0.

The specific gravity of minerals varies between 23·0 (iridium) and 1·4 (natron). The metallic minerals (sulphides, etc.) range mostly from 4·0 (blende) to 10·0 (dyscrasite); but the remainder (oxygen salts) lie mostly between 2 and 5, except those which contain a large proportion of heavy metals (see pp. 556-561).

There are three methods by which the specific gravity may be determined with accuracy.

(*a*) Hydrostatic weighing; (*b*) the use of the pycnometer; (*c*) the use of heavy liquids.

The first requires a considerable mass of the substance (not less than 1·5 to 2·0 grams), which must, moreover, be free from internal cavities; the second is applicable even when less than 1·5 gram is available, but cannot be used for very small masses (less than 0·2 gram); the third requires not more than the minutest fragments, but cannot conveniently be used for minerals whose specific gravity is greater than 3·3.

(*a*) **Hydrostatic Weighing.**—The mineral is suspended by a fine hair or thread from one end of the beam of a chemical balance (the thread having previously been counterpoised); it is weighed first in air and then in distilled water contained in a beaker so placed that the mineral is completely immersed in it.

If W = the weight in air, w = the weight in water, then $W - w$, the loss of weight in water, is equal to the weight of the displaced liquid, *i.e.*

the weight of an equal volume of water. The specific gravity is therefore approximately $\frac{W}{W-w}$. For an accurate determination, however, account must always be taken of the temperature of the water, and its diminished density. If v = the volume of the mineral, d = its density, and Δ_t = the density of water at $t°$ (the temperature of the observation), then $W = vd$; $w = W - v\Delta_t$.

$$d = \frac{W}{W-w}\Delta_t.$$

d here signifies the density of the mineral or the weight of unit volume; its specific gravity is the ratio of this weight to the weight of unit volume of water at 4°. In the metric system the latter (the weight of 1 c.c. of distilled water at 4° C.) is the unit of weight, so that the specific gravity is the same as the density, and is correctly given by the above formula.

The discussion of other corrections to be applied where extreme accuracy is desired, and of the best methods of weighing, will be found in text-books of physics. Of far more importance in the practical determination of the specific gravity of minerals is the selection of pure material, and the precaution that there shall be no air bubbles adhering to the surface of the mineral when it is weighed in water. The influence of intermingled impurities or of internal cavities in such large masses of mineral as are required for this method will often far exceed the correction for temperature. The effect of cavities or adherent bubbles is to give too low a value for the specific gravity. The bubbles can be partly removed by brushing them from the surface of the mineral when it is immersed; but the only way in which they can be completely eliminated is by boiling the water with the mineral in it for about half-an-hour, or by keeping the beaker containing the water and immersed mineral for the same length of time under the exhausted receiver of an air-pump.

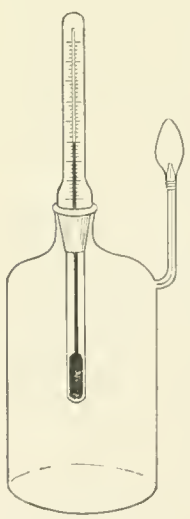


Fig. 372.—Pycnometer.

(*b*) **The Pycnometer.**—This instrument, which is also known by the name of "the specific gravity flask," is a bulb or small flask of glass with a narrow neck, having a ground glass stopper carrying a thermometer; it is also provided with another opening which terminates in an open capillary tube bearing a fine mark near its upper end (Fig. 372). The mineral, having been broken up into small fragments about the size of very small shot, is introduced into the pycnometer and weighed. The pycnometer containing the mineral is next partially filled with water, which is then boiled for some time to expel all air bubbles; it is then placed in a large vessel containing water kept at a constant temperature (say $t°$) and deep enough to cover the part below the neck; after a sufficient time has elapsed to cool the pycnometer and its contents to t, it is filled with water, and the stopper is inserted; this causes the water to overflow through the capillary tube; by means of a tongue

of blotting paper the water which escapes is absorbed, and the level of the column in the capillary tube is brought down to the mark, care having first been taken to thoroughly dry the outside of the flask. It is then weighed again. (If the mineral be too finely powdered some difficulty will be experienced in making it sink to the bottom of the water.)

Finally, the pycnometer is emptied, re-filled with water, the same precautions being observed as in the last operation, and when the column in the capillary tube is reduced to the same height as before, the pycnometer is weighed again. The weight of the empty pycnometer will have been determined at the outset.

If W = weight of the pycnometer containing the mineral; W_1 = weight of the pycnometer containing both water and the mineral: W_2 = weight of the pycnometer containing water alone; P = weight of the pycnometer; then W − P = weight of the mineral in air: $(W_2 - P) - (W_1 - W)$ = weight of the water displaced; and the specific gravity is approximately

$$\frac{W - P}{(W_2 - P) - (W_1 - W)}.$$

If account be taken of the diminished density Δ_t of water at $t°$, then, as before, the specific gravity is

$$\frac{W - P}{(W_2 - P) - (W_1 - W)}\Delta_t.$$

It is very important in using the pycnometer to make sure that the outside is thoroughly dry; the stopper may be slightly greased to prevent any escape of water round its sides, and the observations may be made both with a rising and a falling temperature until the liquid in the capillary tube is in the first case raised and in the second reduced to the mark on the tube.

With due precautions this method is susceptible of great accuracy, and the specific gravity determined with a weight of one gram may be fully relied upon to the third decimal place, provided that a sufficiently small pycnometer be used. The crushing of the mineral into small fragments eliminates to a great extent any error due to internal cavities in the material.

(*c*) **Heavy Liquids.**—If a particle of rock crystal whose specific gravity is 2·65 be immersed in a liquid of exactly the same specific gravity it will neither float nor sink, but will remain suspended at any point within the liquid. The slightest increase in the density of the liquid will cause the particle to rise; the slightest decrease will cause it to sink.

To secure this result a liquid is required of greater density than 2·65, but one which is capable of dilution, so that its density may be reduced to the required extent. The exact specific gravity of the mineral can then be determined by finding that of the liquid when it has been so diluted that the mineral remains suspended in it; and the specific gravity is found by means of the pycnometer as described in text-books of physics.

Methylene iodide is a clear, transparent, brownish liquid, having the specific gravity 3·3 (the mineral babingtonite remains exactly suspended in the undiluted liquid); it may be diluted to any extent with benzol, so that a liquid having any specific gravity between 3·3 and 0·98 (the specific gravity of benzol) may be obtained. Care must be taken that the mixed liquids are well stirred so as to ensure a uniform density. The liquid may be contained in a small glass tube for this purpose, and the minutest fragments of mineral are sufficient.

A very convenient way of measuring the specific gravity with methylene iodide is that devised by Sollas.

Into a long test-tube is poured a small quantity of methylene iodide, and upon this about five times as much benzol. The tube is then allowed to stand for some hours until the two liquids have formed by diffusion a column whose density gradually increases from the surface downwards, consisting mainly of benzol near the top and mainly of methylene iodide near the bottom. The tube must be tightly corked to prevent evaporation of the benzol.

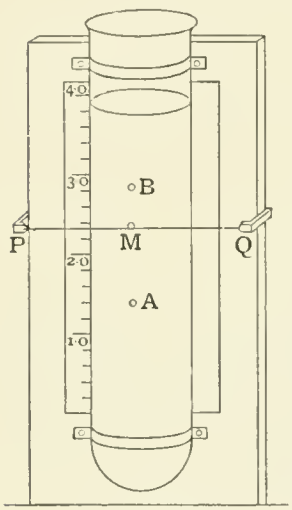


Fig. 373.—Diffusion Column.

A minute fragment of mineral (of specific gravity less than 3·3) being dropped into the tube, remains suspended at a point where the specific gravity of the liquid is equal to its own. Let this be M (Fig. 373).

Now a series of small glass beads or crystals of known specific gravities ranging from 3·3 to 1·0 having been prepared, two of these will be found (by successive trial), one (A) which remains suspended below, and the other (B) above the mineral fragment M.

A scale divided into equal parts being fixed behind the tube the distance between B and M can be compared with that between B and A.

If, then, b be the specific gravity of B, a that of A, and m that of M,

$$\frac{a-m}{m-b} = \frac{\text{AM}}{\text{BM}} \quad \therefore \quad m = \frac{b\text{AM} + a\text{BM}}{\text{AB}}.$$

Thus, if AM = 5 divisions, and BM = 2 divisions, if the specific gravity of B be 2·23, and that of A be 2·98, the specific gravity of M is

$$m = \frac{5 \times 2{\cdot}23 + 2 \times 2{\cdot}98}{7} = 2{\cdot}44.$$

To avoid parallax the scale should be engraved or fixed on a glass mirror fixed behind the test-tube, and the reading should be taken by means of a horizontal wire PQ which can slide in front of the tube, and is viewed so as to coincide with its reflection in the mirror.

The beads may be selected from different kinds of glass or constructed of glass balls or beads made of capillary tubing with platinum wire fused

into them, and their specific gravities may be determined by immersing them in a liquid in which they are just suspended, and determining that of the liquid by means of the Westphal balance.

In practice the chief use of heavy liquids is to identify a mineral fragment by comparing it with others of known specific gravity. Two minerals of very nearly the same density having been found, one of which floats while the other sinks in a liquid in which the mineral under observation remains suspended, it is certain that the latter has a specific gravity intermediate between those of the two known minerals. This is a process of very great value in the determination of minerals, and is very easily applied.

Heavy liquids are also employed to separate the different minerals in a mixture—a crushed rock, for example—by means of their different densities.

Methylene iodide darkens on exposure to light, owing to liberation of iodine, but it may easily be clarified either by freezing the liquid or by shaking it up with a little mercury or potash. This liquid may further be raised to a density of 3·65 by dissolving in it iodoform and iodine.

Other heavy liquids have been recommended, such as solution of potassium-mercuric iodide (Thoulet's or Sonstadt's solution), spec. grav. = 3·196 ; solution of cadmium borotungstate (Klein's solution), spec. grav. = 3·28 ; solution of barium mercuric iodide (Rohrbach's solution), spec. grav. = 3·58. Of these Klein's solution is the most convenient.

A still heavier liquid is that obtained by fusing thallium-silver nitrate, which melts at 70° to a clear liquid and has a specific gravity near 5 ; the density may be reduced by dilution with warm water.

2. **Specific Heat.**—The specific heat of a mineral is the quantity of heat required to raise the temperature of one gram of the substance through one degree centigrade.

This amount must be measured in certain arbitrary units, and the unit of heat always employed is the amount necessary to raise one gram of water through one degree ; this is practically constant for each degree, at any rate between the temperatures 0° and 20°.

To determine the specific heat the mineral is broken into fragments and placed in a small wire basket ; having been raised to a certain temperature in an air bath (which is generally heated by steam) it is then rapidly immersed in a vessel of water of known temperature, and the rise of temperature produced therein is noted by means of thermometers immersed in the water.

If W = weight of the mineral,
t = initial temperature of the mineral,
W_1 = weight of the water,
t_1 = initial temperature of the water,
T = final temperature of the mineral and the water,
x = specific heat of the mineral,

then $(t - T)Wx$ is the number of units of heat lost by the mineral, and this must be equal to $(T - t_1)W_1$, the number of units of heat gained by the water ; the specific heat of water being 1.

Therefore,

$$x = \frac{(T - t_1)W_1}{(t - T)W}.$$

In practice numerous corrections and precautions are required in order to ensure accuracy; allowance must be made for the heat capacities of the wire cage which carries the mineral, and of the vessel which contains the water; a correction must be applied for radiation during the experiment; and some effective method of stirring the water, so that it acquires a uniform temperature, must be adopted. These will be found described in the text-books of physics.

The most delicate and satisfactory apparatus for determining the specific heats of minerals appears to be that known as the "steam calorimeter." In this a known weight of the mineral at a known temperature is immersed in a chamber filled with steam at a known temperature; the specific heat is then calculated from the amount of steam condensed upon the mineral and its wire cage during the time which elapses until they are raised to the temperature of the steam.

For this purpose the mineral is suspended to the beam of a delicate balance and hangs below the balance in a chamber through which a current of steam can be passed; suspended to the same wire which carries the mineral enclosed in a wire basket is a small cone to catch the water which drips from it. The mineral is first weighed as it hangs in the chamber filled with air; steam is then admitted to the chamber, and after a sufficient time has elapsed for the mineral and its carrier to be raised to the temperature of the steam, it is cooled and weighed again; the increase of weight is the weight of the steam condensed upon the mineral and its carrier.

As before, disregarding the corrections,

W = weight of the mineral,
t = the initial temperature of the mineral,
W_1 = weight of the steam condensed,
T = temperature of the steam,
x = the specific heat of the mineral.

Then $(T - t)Wx = W_1\lambda$; where λ is the latent heat of steam, that is to say, the amount of heat evolved in the condensation of one gram of steam to water of the same temperature. (For a description of this instrument and its use see J. Joly, *Proceedings of the Royal Society*, 1887, vol. xli. p. 250, and vol. xlvii. 1890, p. 218.)

Experiment has shown that the specific heat of any compound is closely related to those of its constituents. Determinations of the specific heat may therefore be expected to prove of great value in the interpretation of chemical analyses; they have not been applied to any great extent in mineralogy, and the specific heat has never yet been employed for the identification of minerals, like the specific gravity.

CHAPTER II

THE CHEMICAL PROPERTIES

During a great portion of the first half of the present century, the predominant school of mineralogy was that associated with the names of Werner and Mohs, who were successively professors at the Mining Academy of Freiberg in Saxony. This school endeavoured in systematic mineralogy to employ exclusively the so-called "Natural Historical Properties." Werner's lectures, and a well-known treatise which he published on the External Characters of Minerals, were largely devoted to the study of those characters by which minerals can be identified without the aid of chemical tests. And Mohs, in his *Treatise on Mineralogy* (English translation by Haidinger, 1825), especially defines the natural historical properties as "those with which nature has endowed the bodies which it produces, *provided these properties, as well as the bodies themselves, remain unaltered during their examination.*"

Now, since the chemical characters of any substance may be defined as those which it exhibits during conversion ("chemical change") into some substance which possesses other properties, it is evident that in the hands of these teachers chemistry found little or no application in the study of minerals.

A reaction against such a treatment of the subject was initiated by the influence of Berzelius and the Swedish chemists, and subsequently the chemical properties have come to be held in very different estimation, until at the present time they are regarded as of primary importance.

Modern methods are, of course, totally opposed to the "Natural Historical" spirit in mineralogy; the investigator is bound to examine *all* the available characters of minerals, and among these the chemical composition is quite the most important, whether for purposes of identification, classification or research.

In seeking to identify a mineral it is generally necessary, and always advisable, to sacrifice a portion in order to ascertain its chemical nature, and to determine by the use of various reagents, or with the help of the blowpipe, at least some of the elements which it contains.

Again, the whole basis of classification, originating with that of Berzelius, is a chemical one, and without the knowledge of the composi-

tion it would be impossible to frame any clear conception of the relationships which exist between minerals.

Further, it is from the relations between their chemical and their other properties that the most important advances in scientific mineralogy are to be expected in the future.

A really complete knowledge of the chemical constitution of a mineral, if such be possible, would probably enable us to predict all its other properties.

1. **The Elements in Minerals.**—All the elements which have been isolated by chemists have been found in minerals; many of them are also to be found in animals or vegetables, or in their products; some, like nitrogen, which are of common occurrence among organic substances, are rare among minerals. Carbon, again, which in the form of many different compounds enters into the greater part of organic nature, is comparatively rare in the mineral kingdom, although contained in one large and important series of compounds (carbonates). On the other hand silicon, which is rare among organic materials, is one of the most common constituents of minerals.

It has been estimated that of the materials in the earth's crust, about 47 per cent consist of oxygen, about 27 per cent of silicon, about 8 per cent of aluminium; that iron, calcium, sodium, and potassium are contained in quantities varying from 6 to 2 per cent; while none of the remaining elements amount to more than $\frac{1}{2}$ per cent [Clarke]. Hence oxygen is by far the most important element in the minerals of the earth's crust. Exclusive of gases, only a few elements occur in nature as uncombined or "native" elements; such are carbon, sulphur, arsenic, antimony, bismuth, gold, silver, copper, mercury, tellurium, lead, platinum, iridium, palladium, and iron, and of these the last six are very rare.

Some of the elements exist as important constituents of only a few minerals, but the minerals in which they occur are not necessarily very rare; such are beryllium, bromine, cadmium, chromium, lithium, molybdenum, selenium, tin, titanium, uranium, vanadium, zirconium.

The following elements are important constituents of the minerals in which they are usually contained, but the minerals themselves are exceedingly rare—cæsium, cerium, didymium, erbium, germanium, lanthanum, niobium, tantalum, tellurium, thallium, thorium, yttrium.

The interest of such minerals is mainly due to their being the only source of the above rare elements, and it is chiefly for the investigation of such elements and their compounds that these minerals have been sought and studied.

2. **Atomic Constitution of Minerals.**—It is not the purpose of the present chapter to give any account of the principles of chemistry, which are to be found in the text-books of that subject; but rather to indicate the chief features of the chemistry of minerals as compared with that of other substances. It will be made clear in a subsequent chapter that the chief difficulties which beset the study of mineral chemistry are due to the fact that the materials investigated have not been prepared from known compounds in the chemist's laboratory, but have been made by

nature from the vast mixture of materials existing in the earth's crust and under widely varying conditions; hence minerals are not in general simple pure compounds, but are for the most part complicated by numerous impurities, or are often, at the best, isomorphous mixtures (see p. 225). To eliminate the impurities, or to trace the simple compounds of which these mixtures consist, and to determine the nature and constitution of the species to which they can be referred, is the task of the mineral chemist.

When a substance can, by change of pressure and temperature, be converted from a solid to a liquid, from a liquid to a gas, and *vice versâ* (like ice, water, and steam), it is regarded as retaining its identity in the three states; it is often assumed that the molecule of the solid is an aggregation of the gaseous molecules, and is to be expressed as a multiple of the latter.

Recent research seems, however, to indicate that the crystal molecule is by no means so large a multiple of the gaseous molecule as was formerly supposed, and in fact that it may in some cases be identical with it.

The formula of the gaseous molecule itself, commonly known as the "molecular formula" of the substance, would be ascertained if the vapour density of the mineral could be found; but almost all minerals are solids which cannot be vaporised, so that little or nothing is known yet of their gaseous molecules, and even if known the molecular formula would not necessarily explain the constitution of the crystallised mineral.

The formulæ by which minerals are denoted, represent, therefore, as a rule, little more than the relative proportions of the elements which they contain, and are merely an expression of the percentage composition as determined by analysis, translated into the language of atomic proportions where possible.

Thus barytes is denoted by the symbol $BaSO_4$, which (since the atomic weight of barium is 137, of sulphur 32, and of oxygen 16) indicates that the mineral consists of these three elements in the following proportion by weight—

$$\begin{aligned} Ba &= 137 \\ S &= 32 \\ O_4 &= 64 \\ \hline & 233 \end{aligned}$$

or in percentages,

$$Ba = \frac{137}{233} \times 100 = 58{\cdot}8$$

$$S = \frac{32}{233} \times 100 = 13{\cdot}7$$

$$O = \frac{64}{233} \times 100 = 27{\cdot}5$$

$$\overline{100{\cdot}0}$$

Such a formula, which denotes no more than the relative proportions of the elements, and is therefore only sufficient to give the theoretical percentage composition of a mineral corresponding to its analysis, constitutes the "Empirical Formula."

From the percentage composition as given by quantitative chemical analysis, the empirical formula is of course found by the inverse process of dividing the percentage of each element by its atomic weight, thus—

$$\frac{58{\cdot}8}{137} = {\cdot}429 = \text{the number of atoms of Ba.}$$

$$\frac{13{\cdot}7}{32} = {\cdot}429 \quad \text{,,} \quad \text{,,} \quad \text{S.}$$

$$\frac{27{\cdot}5}{16} = 1{\cdot}7187 \quad \text{,,} \quad \text{,,} \quad \text{O.}$$

But in whole numbers ·429 : ·429 : 1·7187 = 1 : 1 : 4 ; therefore the empirical formula is $BaSO_4$.

The law of definite combining proportions is now so well established that no doubt can be entertained of the possibility of referring every mineral to one or more definite empirical formulæ like the above. Yet it must not be denied that at present for very many minerals individual analyses do not lead to simple formulæ, or even to atomic proportions; the difficult problem which has to be solved by the mineral chemist is the reduction of widely varying and complicated analyses to simple atomic proportions and simple empirical formulæ. This has been so successfully accomplished for some complex minerals (such as tetrahedrite, pyroxene, felspar) that we may expect with perfect confidence the ultimate reduction of all mineral species to rational, and probably also to simple, formulæ.

The establishment of *molecular* formulæ is a problem of a higher order, towards which very little progress has yet been made.

3. **Equivalence of Atoms in Minerals.**—Confining our attention for the present to those minerals whose analyses lead to definite simple formulæ, it will be found, when their empirical formulæ are compared, that many of them are similar and only differ in having a certain number of atoms of one element in the one substituted for a certain number of atoms of another element in the other; thus barytes, $BaSO_4$, is related to anglesite, $PbSO_4$, and both are obviously related to potassium sulphate (aphthitalite), K_2SO_4, and to sulphuric acid, H_2SO_4; the one may be derived from the other by the interchange of the atoms, or atomic groups Ba, Pb, K_2, H_2.

Generally speaking, two atoms of a monad element may replace one of a dyad element; three of a dyad element may replace two of a triad, and so on, to form a series of compounds which may conveniently be classed together; in this instance as "sulphates."

(Further observation shows, however, that in minerals, as in other compounds, the valency of an element is not always the same; it may, for

instance, in one substance act as a triad, and in another as a dyad; the most conspicuous example is iron, which may occur either in the ferrous (dyad) or the ferric (triad) condition.)

It is important, then, in comparing the chemical characters of different minerals to base their classification upon some classification of the elements which they contain. For different purposes in mineralogy it is convenient to distinguish the elements as metallic and non-metallic, or as electro-positive and electro-negative (although the latter terms can only be used in a relative sense), or to group them according to their valencies as monads, dyads, etc., but the mineralogist generally uses the familiar classification of the elements by their atomic weights as in the accompanying table of Mendeleef.

The properties of the elements, both physical and chemical, being periodic functions of their atomic weights, the most closely allied elements are brought into corresponding positions in the table. Hence it is not surprising to find that this table indicates also many remarkable analogies between mineral compounds.

	I	II	III	IV	V	VI	VII	VIII
1	H							
2	Li	Be	B	C	N	O	F	
3	Na	Mg	Al	Si	P	S	Cl	
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe, Ni, Co
5	Cu	Zn	Ga	Ge	As	Se	Br	
6	Rb	Sr	Y	Zr	Nb	Mo		Ru, Rh, Pd
7	Ag	Cd	In	Sn	Sb	Te	I	
8	Cs	Ba	La	Ce	Di			
9				Tb	Er			Sm, Ms
10			Yb		Ta	W		Os, Ir, Pt
11	Au	Hg	Tl	Pb	Bi			
12				Th		U		

Minerals which are corresponding compounds of elements in one of the vertical columns often exhibit a great similarity to one another; further,

a greater similarity exists between compounds of alternate elements in any one vertical column than between those of consecutive elements, since the elements which are most closely united in their properties are those contained either in one of the even periods or those contained in one of the odd periods.

Thus certain minerals containing magnesium, calcium, zinc, strontium, cadmium, and barium are closely allied ; but the corresponding compounds of calcium, strontium, and barium resemble each other far more closely than they resemble those of magnesium, zinc, and cadmium (see the Barytes Group, the Calcite Group, the Aragonite Group).

Corresponding compounds of the elements belonging to the odd series 1, 3, 5, 7, 9, 11, in any one vertical column, are sometimes called "eutropic." Corresponding compounds of those which belong to the even series, *e.g.* Li, K, Rb, Cs, constitute another "eutropic" set. Such eutropic sets are very closely allied in all their properties.

It will be noticed again that with the exception of carbon and the elements of the so-called transitional groups in column VIII., all the elements mentioned above as occurring native (or uncombined) belong to the odd series. Again, the well-defined groups of minerals described below as "metallic" (those having a metallic lustre) are almost exclusively compounds of the metals Cu, Zn, Ge, Ag, Cd, Sn, Au, Hg, Tl, Pb, belonging to the odd series, combined with sulphur or selenium, or the three allied elements, As, Sb, Bi.

Many other mineralogical relations are disclosed by this table, and are illustrated by the part which the different elements play in the composition of the various minerals to be subsequently described (see p. 217).

Some of the most distinct sub-groups in relation to mineralogy are :—

In Group I.—(1) the alkali metals, Li, Na, K, Rb, Cs.
(2) the metals Cu, Ag.
In Group II.—(1) metals of the alkaline earths, Ca, Sr, Ba.
(2) the metals Zn, Cd, Hg.
In Group IV.—the elements Si, Ti, Ge, Zr, Sn, Th.
In Group V.—the elements P, V, As, and again As, Sb, Bi.
In Group VI.—the elements S, Se, Te.
In Group VII.—the haloid elements, F, Cl, Br, I.
In Group VIII.—the elements Fe, Ni, Co.

4. **Equivalence of Radicles in Minerals.**—In compounds which consist of more than two elements, as is the case with most minerals, the elements may conveniently be regarded as associated to form separate groups, which, like the elements, are capable of replacing one another in different compounds. These groups or "Radicles," like the elements, have sometimes been distinguished as electro-positive and electro-negative, and each has a certain valency ; they may be regarded as replacing each other, or as replacing elements of the same valency. Thus in rock salt, NaCl, as compared with sal-ammoniac, NH_4Cl, the atomic group NH_4 may be regarded as a monad radicle, and capable of replacing the metal

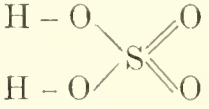
sodium in association with the haloid element chlorine. In calcite, $CaCO_3$, as compared with anhydrite, $CaSO_4$, both CO_3 and SO_4 may be regarded as dyad radicles, each capable of combining with the dyad element Ca.

A compound radicle (so-called to distinguish it from an element) is generally supposed to consist of several atoms, so combined that one or more of their combining capacities or "bonds" are unsatisfied, and the valency of the radicle is determined by the number of unsatisfied bonds; thus hydroxyl, H – O – , is a monad radicle, and one of great importance in the chemical structure of minerals.

Formulæ which show how the atoms may be grouped together to form certain radicles are called "constitutional" formulæ, and when the formula indicates by means of bonds the mode in which the atoms are supposed to be linked together by their combining capacities, it is called a "structural" or "graphic" formula; thus for sulphuric acid :—

Empirical Formula— H_2SO_4
Constitutional Formula— $SO_2(OH)_2$

Graphic Formula—



The radicles whose existence is assumed in order to explain the constitution of most minerals are either hypothetical, or are founded upon experiments with other compounds, both inorganic and organic, in the laboratory, and the graphic formula in many cases is based upon very slight evidence. Nevertheless such formulæ are used very generally to indicate possible relations between minerals having similar characters.

5. **Classification of Minerals by Acid Radicles.**—By their chemical characters minerals are separated into certain large groups, according to the non-metallic elements or radicles which they contain, as follows :—

1. Elements.
2. Haloid compounds in which metallic elements or radicles are combined with the haloid elements, fluorine, chlorine, bromine, and iodine.
3. Sulphides, in which metallic elements or radicles are combined with sulphur.
4. Sulpho-salts, which may be derived from certain sulpho-acids (see § 8).
5. Oxides and hydroxides, in which metallic elements or radicles are combined with oxygen and with hydroxyl, OH, respectively.
6. Oxy-salts, which may be derived from certain oxy-acids (see § 8).

Each of these groups contains a number of sub-groups, to be considered below.

The terms acids, bases, and salts are freely used in mineral chemistry in the commonly accepted sense, but without the experimental basis upon

which the distinctions have been made in the case of the more tractable compounds familiar to chemical students.

In an oxy-acid the hydrogen, which is capable of being replaced by metals or by compound radicles to form a salt, is supposed to be present as a constituent of hydroxyl, OH; and in a sulpho-acid the replaceable hydrogen is supposed to be present as a constituent of the radicle SH.

A mineral such as barytes is thus intelligibly described as a salt of sulphuric acid, $(OH)_2SO_2$, in which the two atoms of hydrogen have been replaced by one of the dyad barium.

All the silicates are oxy-salts, and are referred to certain silicic acids; these should be distinguished in the usual way as monobasic when there is only one replaceable hydrogen atom; dibasic when there are two, and so on; but in reality very little is known of the nature or even of the existence of these acids.

Again, the term "base" is used to signify the oxide of the metallic element in an oxy-salt; but it is not always possible to say whether a given element, situated in the central columns of the table of p. 199, is to be regarded as playing the part of a base or an acid in a mineral. This is especially true among the large and important group of silicates of aluminium, boron, titanium, zirconium (and tin), concerning which opinions have been much changed during recent years, so that these elements come to be regarded as entering into the acid radicle in many minerals in which they were formerly called bases.

The following are some of the chief acids required to make the composition of the more important minerals intelligible; the salts derived from them receive their names from the radicle which the acid contains.

Sulpho-acid—

$(SH)_3As = H_3AsS_3$, from which are derived sulpharsenites; with corresponding compounds of antimony and bismuth.

Oxy-acids—

$(OH)NO_2 = HNO_3$, from which are derived nitrates. One corresponding compound of iodine is also known.

$(OH)_2CO = H_2CO_3$, from which are derived carbonates.

$(OH)_2SO_2 = H_2SO_4$, from which are derived sulphates; with corresponding compounds of chromium.

$(OH)_2WO_2 = H_2WO_4$, from which are derived tungstates; with corresponding compounds of molybdenum.

$(OH)AlO = HAlO_2$, from which are derived aluminates; with corresponding compounds of iron and chromium.

$(OH)BO = HBO_2$, from which are derived (meta-)borates.

$(OH)_3PO = H_3PO_4$, from which are derived phosphates; with corresponding compounds of arsenic and vanadium.

$(OH)_4Si = H_4SiO_4$, from which are derived (ortho-)silicates }
$(OH)_2SiO = H_2SiO_3$, from which are derived (meta-)silicates } with corresponding compounds of titanium and zirconium.

$(OH)TaO_2 = HTaO_3$, giving rise to (meta-)tantalates; with corresponding compounds of niobium.

The following important inorganic salts are scarcely or not at all represented among minerals: chlorates, chlorites, sulphites, arsenites, nitrites, phosphites; also phosphides, carbides. Owing to the conditions under which minerals exist in the crust of the earth, such unstable or soluble compounds as these, if they are occasionally formed by natural processes, can scarcely survive as minerals, but are quickly decomposed or carried away in solution. Some of them exist in meteorites, which have probably been formed under very different conditions.

6. **Normal, Acid, and Basic Salts.**—The salts derived from any of the acids mentioned above are further grouped into three subdivisions. The first or normal salts are those in which all the replaceable hydrogen of the acid is replaced; thus barytes, $BaSO_4$, is a normal salt of sulphuric acid, H_2SO_4; calcite, $CaCO_3$, is a normal salt of carbonic acid, H_2CO_3.

The acid salts, on the other hand, are those in which only a part of the hydrogen of the acid is replaced; thus misenite, $KHSO_4$, is acid potassium sulphate, having only half the hydrogen replaced by the metal potassium. Basic salts are such as contain more basic atoms or radicles than are required to replace the hydrogen of the acid. Thus malachite, $Cu_2(OH)_2CO_3$, and chessylite, $Cu_3(OH)_2(CO_3)_2$, are both basic copper carbonates.

Acid salts are rare among minerals, except perhaps among the silicates, but instances of basic salts are common.

7. **Molecular Compounds: Water of Crystallisation.**—In some minerals the composition is conveniently expressed as the association of two or more distinct molecules united by some connection different from that which unites the atoms or radicles in each molecule. Thus kalinite or potash alum, of which the empirical formula is $KAlS_2H_{24}O_{20}$, is often regarded as a molecular compound, and is expressed by the formula $Al_2(SO_4)_3 . K_2SO_4 . 24H_2O$; this suggests that the potassium sulphate, the aluminium sulphate, and the water exist as such in the compound, and are not united exactly as the radicles within each of the three groups, but in some other way.

Compounds of this nature are called "Molecular Compounds" or "Double Salts." In the case of kalinite this view receives some support from the fact that in a solution of the salt the two sulphates may be separated by the mechanical process of diffusion. On the other hand, this experiment only indicates that the two sulphates are separated in the state of *solution;* the molecular formula, while possibly that of the liquid molecules, is not necessarily that of the crystal molecules of the alum.

Other instances of minerals which are often regarded as double salts are matlockite, $PbCl_2 . PbO$; glauberite, $Na_2SO_4 . CaSO_4$; dolomite, $CaCO_3 . MgCO_3$.

Many of the basic salts may with equal propriety be described as double salts; *e.g.* malachite as $CuCO_3 . Cu(OH)_2$. The distinction between a molecular compound and an atomic compound is only to be established by experiments upon the behaviour of the substance in solution, —experiments which can rarely be made upon minerals.

At the present time there is very little evidence to prove whether any given mineral is to be regarded as a molecular compound or not.

When, however, one or more of the molecules in such a compound are molecules of water, it is possible to a certain extent to invoke experimental evidence and to draw a distinction. Many minerals yield water when heated; now this may either be present in the mineral as such, or it may result from the association of hydrogen and oxygen contained in the mineral, and be set free on heating.

Sometimes, however, the water is given off at a temperature below 100°; sometimes at higher temperatures; sometimes only at red heat. When the water is given up below 100° as though by evaporation, it is usually regarded as "water of crystallisation," *i.e.* water which is present as such in the mineral. This often appears to be united scarcely, if at all, more tenaciously than the separate molecules in ordinary water, and therefore is not regarded as bound by free valencies.

Salts which yield water are said to be hydrated; those which do not yield water are called anhydrous. The term hydrated is sometimes confined to those which contain water as such.

The same salt is often capable of combining with several different proportions of water; sodium sulphate crystallised from solution at different temperatures yields, as is well known, crystals containing either seven or ten molecules of water; these are totally distinct substances, and differ in their crystalline forms.

That the water is not united so tenaciously as the other constituents of a hydrated salt is evident from the fact that it can be in many instances more easily removed; many salts give up their water if exposed to dry air at ordinary temperatures. Still more remarkable is the property which some substances possess of reabsorbing water after it has been removed. Gypsum, $CaSO_4 . 2H_2O$, loses most of its water at a temperature of 160°, and this is reabsorbed when the substance is moistened. It appears, therefore, that water of crystallisation is not necessarily given up below 100°.

So also some of the zeolites when heated give up a part or all of their water and acquire new optical properties; but when immersed in water they absorb exactly the same amount, regaining at the same time the optical and other characters of the hydrated salt. In such instances we have a molecule H_2O, which can either be put into or taken out of the mineral, and is therefore supposed to be present as such in the hydrated compound.

On the other hand, the water which is only given off at high temperatures can scarcely be present in the compound in the same manner as the water of crystallisation, and is therefore distinguished as "water of constitution"; this is generally supposed not to exist in the mineral as water, but to result from the union of hydrogen and oxygen, or from hydroxyl, contained in the compound.

Thus malachite has the empirical formula $Cu_2H_2CO_5$, and since the water is only given off at a high temperature the mineral is regarded as

a basic carbonate $CuCO_3 . Cu(OH)_2$ or $(CuOH)_2CO_3$, in which the water is all water of constitution.

In other minerals the water may be partly constitutional, which is given off at high temperatures, and partly water of crystallisation.

In chalcanthite, $CuSO_4 + 5H_2O$, four molecules of the water are given off at 100°, and the fifth at 200°, so that the latter is possibly combined in some manner different from the former. The formula, if written in the shape $(CuOH)HSO_4 . 4H_2O$, serves to indicate this behaviour.

Epsomite, $MgSO_4 . 7H_2O$, gives off six molecules of water at 132°. The seventh molecule is only given off at 210° and is held much more tenaciously. The heat of hydration of the substance confirms this difference between one molecule of water and the remaining six. Its behaviour may be expressed by the formula $H(MgOH)SO_4 . 6H_2O$.

In such cases as these a constitutional formula is very useful as indicating a real experimental fact, and it is not necessary to regard it as doing more than this. But in those cases in which successive proportions of water are given off at different temperatures, it is quite impossible to draw a distinction between the water of crystallisation and constitutional water. For example, in heulandite, $CaAl_2Si_6O_{16} . 5H_2O$, the water is given off gradually between 100° and 400°.

In the formulæ used in this book the water which is given off at a *relatively* low temperature is expressed as H_2O, and united with the formula as one of the molecules of a molecular compound; that which is given off at a *relatively* high temperature is incorporated in the formula as water of constitution.

8. **Basicity of Acids.**—When an attempt is made to arrange minerals according to their acid radicles, as indicated in the table on p. 202, a difficulty is encountered in several of the groups because the formulæ cannot be made to fall into the exact form there given. Thus, as shown in the table, the silicates cannot all be conveniently referred to the acid $(OH)_4Si$; many silicates, for example, are more naturally referred to an acid $(OH)_2SiO$.

Minerals belonging to the former class are called orthosilicates to distinguish them from the latter, which are called metasilicates, and of the two acids the one is tetrabasic and the other is dibasic.

A similar difficulty is met with in other groups, especially among the sulpho-salts and the borates; these groups contain minerals which must be referred to various acids differing in their basicity. Now when the various oxy-acids which must be assumed in any group are arranged in order of their basicity they are found to differ by multiples of H_2O. Hence these oxy-acids are generally regarded as derived from the normal acids by the removal of a certain number of molecules of H_2O.

Thus among the borates are to be found the following minerals:—

Pinnoite, $MgB_2O_4 . 3H_2O$,	corresponding to the acid		$(HO)BO$.
Borax, $Na_2B_4O_7 . 10H_2O$,	„	„	$(HO)_2B_4O_5$.
Colemanite, $Ca_2B_6O_{11} . 5H_2O$,	„	„	$(HO)_4B_6O_7$.

Here the acid of borax may be derived from that of pinnoite by removing one molecule of water from four of the former, thus—

$4HBO_2 - H_2O = H_2B_4O_7$; the acid of colemanite by removing one molecule of water from six of the same—$6HBO_2 - H_2O = H_4B_6O_{11}$.

Among the sulpho-salts (sulpharsenites, sulphantimonites, sulphobismuthites) there is a still greater variety of hypothetical acids which are derived from the normal tribasic acid H_3AsS_3 in a similar manner by differences of H_2S. Those which are less basic (more acid) are derived by the removal of molecules of H_2S; those which are more basic by the addition of such molecules.

The following are a few of the many types of sulpharsenites known among minerals:—

$$HAsS_2 = As(SH)_3 - H_2S.$$
$$H_4As_2S_5 = 2As(SH)_3 - H_2S.$$
$$H_3AsS_3 = As(SH)_3.$$
$$H_8As_2S_7 = 2As(SH)_3 + H_2S.$$
$$H_{10}As_2S_8 = 2As(SH)_3 + 2H_2S.$$

Similarly, among the silicates the following acids, derived in the same manner from orthosilicic acid, H_4SiO_4, are sometimes assumed in order to account for the constitution of the many and important minerals included in the group.

$$H_2Si_2O_5 = 2Si(OH)_4 - 3H_2O.$$
$$H_4Si_3O_8 = 3Si(OH)_4 - 4H_2O.$$
$$H_2SiO_3 = Si(OH)_4 - H_2O \quad . \quad . \quad . \quad \text{Metasilicic acid.}$$
$$H_8Si_3O_{10} = 3Si(OH)_4 - 2H_2O.$$
$$H_6Si_2O_7 = 2Si(OH)_4 - H_2O.$$
$$H_4SiO_4 = Si(OH)_4 \quad . \quad . \quad . \quad . \quad . \quad \text{Orthosilicic acid.}$$

Here, however, and in any such complicated group, it is not really possible to say whether a given mineral is a normal salt of a certain acid, or an acid salt of a more basic acid, or a basic salt of a less basic acid. Thus, if there were no other evidence as to its composition it would be impossible to say whether hemimorphite, $Zn_2H_2SiO_5$, is a basic metasilicate, to be expressed as $(ZnOH)_2SiO_3$, or an acid salt of a distinct acid H_6SiO_5, derived from orthosilicic acid by the addition of one molecule of H_2O. In this case, however, there is no evidence of the existence of an acid of the type H_6SiO_5.

Both in the sulpho-salts and the silicates great doubt exists at the present time as to the acids to which minerals are to be referred. None of the hypothetical acids given above for sulpho-salts has been proved to exist independently. Of those which are assumed to explain the series of the silicates, some silicic acids of which salts or ethers have been prepared are — orthosilicic acid, $(OH)_4Si$; metasilicic acid, $(OH)_2SiO$; and the acid $(OH)_6Si_2O$.

9. **Classification of the Silicates.**—The preceding remarks will have made it clear that in regard to minerals very little experimental evidence is yet available which can throw any light upon their constitution. The percentage composition having been ascertained by quantitative analysis, little at present can be done towards establishing constitutional formulæ,

except to compare minerals with any of the more tractable compounds to be made or experimented upon in the laboratory, especially such as are volatile and soluble, to which they may be in some way allied. Mineralogy is to a large extent the chemistry of silicon compounds—about half the minerals known are silicates—but unfortunately it has not yet proved possible to apply to these any of the methods which have been so fruitful in the study of the carbon compounds in organic chemistry; their constituents cannot be replaced by organic radicles, nor can series of derivatives be prepared; their vapour density cannot be determined, nor their physical behaviour in solution. We have to content ourselves with the analogies that they may present with other compounds which are better understood, or the relations that they bear to each other.

In a descriptive science like mineralogy mutual relations may well be brought to light by testing various schemes of classification, just as in zoology or botany the essential relationships between various animals or various plants have been gradually discovered by testing different systems of classification until the most satisfactory arrangement into species and genera has been evolved.

It has already been stated that the main grouping of minerals is into such classes as carbonates, phosphates, and silicates by means of the non-metallic radicles which, in accordance with the general principles of experimental chemistry, they are supposed to contain; and that on account of the similarity and equivalence of their elements the class of phosphates, for example, is coupled with arsenates and vanadates, and the class of silicates with titanates and zirconates.

The difficulties which are as yet experienced in subdividing satisfactorily within these large groups on any chemical principle alone may be illustrated by some of the methods which are in actual use at the present time in classifying the important but difficult class of silicates.

(1) *By the Oxygen Ratio.*—This classification simply depends upon the atomic ratio of the oxygen of the silica to that of the bases.

Whatever may be the type of acid to which a silicate is referable, the nature of a salt, as stated above, renders it clear that any silicate can be expressed as certain metallic oxides or bases combined with a certain amount of silica. Thus an orthosilicate R''_2SiO_4 is expressible as $2R''O . SiO_2$, in which the base contains two atoms of oxygen and the silica contains also two atoms of oxygen; the oxygen ratio is therefore 1 : 1, and such compounds may be called unisilicates.

A metasilicate $R''SiO_3$ or $R''O . SiO_2$ has the oxygen ratio 1 : 2, and may be called a bisilicate.

Among silicates are also to be found as an important group trisilicates of the type $R''_2Si_3O_8$ or $2R''O . 3SiO_2$, in which the ratio is 1 : 3.

Those minerals in which the oxygen ratio is greater than 3 are usually classed together as polysilicates; and those in which the oxygen ratio is less than 1 are called subsilicates.

An arrangement of this difficult group of minerals in order of the oxygen ratios has the advantage of avoiding to a great extent any theoretical views as to the structure of the silicate or any prejudice

regarding the acid of which it is a salt. It merely expresses the result of analysis and in an extremely convenient form, for the analytical result is always given in percentages of the various oxides.

That the oxygen ratio may fail to indicate true relationships may be seen from the following three minerals, of which the empirical formulæ are perfectly well established :—lime-garnet, albite, and anorthite.

Lime garnet.		Albite.		Anorthite.	
CaO . .	37·3	Na_2O . .	11·8	CaO . .	20·1
Al_2O_3 . .	22·7	Al_2O_3 . .	19·5	Al_2O_3 . .	36·7
SiO_2 . .	40·0	SiO_2 . .	68·7	SiO_2 . .	43·2

From these percentages the empirical formulæ are—

Lime garnet . . . . . $3CaO . Al_2O_3 . 3SiO_2$ or $Ca_3Al_2Si_3O_{12}$.
Albite . . . . . $Na_2O . Al_2O_3 . 6SiO_2$ or $NaAlSi_3O_8$.
Anorthite . . . . . $CaO . Al_2O_3 . 2SiO_2$ or $CaAl_2Si_2O_8$.

According to their oxygen ratio, therefore—

Lime garnet is a unisilicate ; ratio 1 : 1.
Albite „ trisilicate ; ratio 3 : 1.
Anorthite „ unisilicate ; ratio 1 : 1.

In reality, however, nothing can be more certain than that albite and anorthite are very closely related by all their properties, while garnet is a mineral quite distinct from them. It has been suggested that an alkaline base, such as soda, involves the presence of an excess of silica as compared with a non-alkaline base, such as lime.

Moreover, it is very difficult to feel sure that certain weak bases, such as aluminium and (ferric) iron may not equally well belong to the acid as to the basic part of the silicate, so that there is no certain ground for referring them to the one or the other side of the oxygen ratio.

(2) *As Salts of various Silicic Acids.*—Many of the natural silicates may be normal salts of the following possible silicic acids :—

H_4SiO_4—orthosilicates ; example, olivine Mg_2SiO_4.
H_2SiO_3—metasilicates ; example, enstatite $MgSiO_3$.
$H_6Si_2O_7$—orthodisilicates ; example, barysilite $Pb_3Si_2O_7$.
$H_2Si_2O_5$—metadisilicates ; example, titanite $CaSiTiO_5$.

Most known silicates which occur in nature can be referred to one or other of these acids as normal, acid or basic salts, either hydrated or anhydrous, or as molecular compounds.

If the three minerals mentioned above are to be referred to these four acids—

Lime garnet would be regarded as a normal orthosilicate, $Ca_3Al_2(SiO_4)_3$.

Albite as a normal salt (metasilicate and metadisilicate?), $NaAlSi_3O_8$, in which H_4 of the acid $H_4Si_3O_8 (= H_2SiO_3 + H_2Si_2O_5)$ is replaced by the tetravalent metallic group $NaAl$.

Anorthite as a normal orthosilicate, $CaAl_2(SiO_4)_2$.

But here again the close relationship which undoubtedly exists between albite and anorthite finds no expression. If one is to regard them as similar salts, the radicle SiNa of albite must be replaced by the radicle AlCa of anorthite, so that, as suggested above, Al plays the part of an acid.

(3) *As Substitution Derivatives of Normal Aluminium Silicates.*—Most of the natural silicates are compounds containing aluminium, and F. W. Clarke has endeavoured to express all the minerals of this group as substitution derivatives of such compounds as the normal aluminium orthosilicate $Al_4(SiO_4)_3$, in which one or more of the aluminium atoms can be replaced by trivalent radicles, or by groups of divalent or monovalent radicles.

According to this view—

Lime garnet is $Al_2Ca_3(SiO_4)_3$.
Anorthite is $Al_6Ca_3(SiO_4)_6$.

Both are orthosilicates, and the latter is derived from $2Al_4(SiO_4)_3$ by replacing Al_2 by Ca_3.

Albite is $Al_3Na_3(Si_3O_8)_3$,

and is to be regarded as derived from another normal salt whose formula is $Al_4(Si_3O_8)_3$, so that even here a second acid must be introduced into the scheme.

For, clearly, if albite and anorthite are to have any close chemical relationship the acids H_4SiO_4 and $H_4Si_3O_8$ must be regarded as analogous, and therefore the acid radicle SiO_4 as replaceable by and equivalent to the acid radicle Si_3O_8.

(4) *As Substitution Derivatives of Multiples of Silica.*—Goldschmidt has suggested that all silicates may conveniently be referred to the type $mSiO_2 + nR$, where one or more atoms of Si may be replaced by other tetravalent radicles, and where R is some molecule such as NaCl, or H_2O, which is generally not a silicate. Thus, as compared with quartz, SiO_2, which may be regarded either as $8SiO_2$, *i.e.* Si_8O_{16}, or as Si_6O_{12},

Albite is $Si_6(NaAl)_2O_{16}$,
Anorthite is $Si_4(CaAl_2)_2O_{16}$,
Lime garnet is $Si_3Ca_2(CaAl_2)O_{12}$.

In all these instances, without proceeding so far as to assign graphic formulæ, an attempt is made to show how the atoms can be grouped into mutually replaceable radicles in a manner consistent with the nature of the whole group of silicates.

It will now, however, be clear from the examples given that all such attempts are of a highly speculative nature; it is impossible to say without accurate determinations of at least the specific heat, molecular volume, and other physical properties, whether albite is $NaAlSi_3O_8$ or $Na_2Al_2Si_6O_{16}$; still less is it possible to ascertain the acid of which it is a salt without the comparison of other and more tractable salts (organic if

possible) of the same acid; and the molecular constitution of the mineral can scarcely be ascertained without some knowledge of its behaviour in the presence of various chemical reagents or of the several processes by which it may be artificially prepared.

It is also clear that minerals such as albite and anorthite are classed together, not solely, or indeed at all, on account of their chemical similarity, but because, by reason of their other properties, they are first known to be closely related; an effort is then made, by manipulating the empirical formula, to express the relationship by means of the mutual replacement of equivalent radicles.

To this extent, then, the natural history methods of Werner and Mohs, mentioned at the beginning of this chapter, were completely justified; these mineralogists never had any hesitation in classifying together albite and anorthite under one mineral group—felspar—because by all their external characters they are clearly very intimately related to one another; it was therefore fortunate in the order of events that a natural history classification should have preceded a more chemical system, and that mineralogists became more or less agreed upon which minerals belonged to the same group before attempting to explain why they were to be classed together.

The modern classification of minerals, though apparently chemical, is by no means purely so, and we are at once driven to the subject of the next book—the relationship between the chemical and physical properties.

Further, it must be remembered that up to the present our attention has been entirely confined to those minerals whose analyses lead to simple rational atomic proportions for the elements which they contain. In reality, however, most mineral analyses lead to proportions which are not in the ratio of simple numbers of atoms of one element to those of another, as in the case of the analyses quoted above.

This and the preceding difficulties can only be overcome by the great principles of isomorphism and of the mixtures of crystallised solids which we proceed to consider in Book III.

If the present chapter appears to have merely indicated how little is known of the composition of the simple minerals themselves beyond their empirical formulæ, the next chapter will show how much has been discovered which at any rate expresses the composition of the complicated minerals in terms of the simpler.

BOOK III

THE RELATIONS BETWEEN THE PROPERTIES OF MINERALS

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1. **Isomorphism, Polymorphism, and Vicarious Replacement.**—That there is a relation between the form of a crystal and its composition was first distinctly shown by Mitscherlich in 1819 in his researches upon the phosphates and arsenates of potassium and ammonium. He proved, for instance, that the acid phosphate of ammonium possesses what is apparently the same crystalline form as the acid arsenate of ammonium; and these two substances are clearly also similar in their chemical composition.

Two substances which have a similar composition and the same or nearly the same crystalline form were called "isomorphous."

Among minerals the group of rhombohedral carbonates

Calcite . . .	$CaCO_3$
Magnesite . . .	$MgCO_3$
Chalybite . . .	$FeCO_3$
Calamine . . .	$ZnCO_3$
Rhodochrosite . . .	$MnCO_3$

were regarded as a typical instance of isomorphous compounds.

Further, Mitscherlich subsequently showed (1821) that an element or compound may occur in two (or more) distinct forms. Sulphur, for example, exists both in orthorhombic and in several sorts of monoclinic crystals.

A substance which can crystallise in two or more distinct forms was called "dimorphous" or "polymorphous."

Among minerals

Calcite . . .	$CaCO_3$—Hexagonal
Aragonite . . .	$CaCO_3$—Orthorhombic

afford a typical instance of a dimorphous compound;

Anatase . .	TiO_2—Tetragonal
Rutile . .	TiO_2—Tetragonal with axes different from those of anatase
Brookite . .	TiO_2—Orthorhombic

of a trimorphous compound.

A very important suggestion had been made a short time previously by Fuchs, who pointed out that in the mineral gehlenite, although it is essentially a silicate of calcium and aluminium ($3CaO . Al_2O_3 . 2SiO_2$), a certain proportion of oxide of iron is present, and that this may be regarded as replacing a certain proportion of lime; if, therefore, the composition of the mineral is to be expressed by simple numbers, the sum of these two constituents, and not their individual proportions, must be taken into account. "I believe," he says, "that, in the future, varieties will be found which contain less or even no oxide of iron, but a larger quantity of lime."

The constituents which can thus replace one another in a compound were called "vicarious" constituents.

Among minerals the garnet group offers a typical example of vicarious constituents. In the following garnets

Grossular	$3CaO . Al_2O_3 . 3SiO_2$
Pyrope	$3MgO . Al_2O_3 . 3SiO_2$
Almandine	$3FeO . Al_2O_3 . 3SiO_2$
Andradite	$3CaO . Fe_2O_3 . 3SiO_2$
Uvarovite	$3CaO . Cr_2O_3 . 3SiO_2$

the oxides CaO, MgO, FeO are one set of vicarious constituents, and the sesquioxides Al_2O_3, Fe_2O_3, Cr_2O_3 are another set; while other garnets may contain some of each.

Upon these three facts—

(1) Similar compounds have nearly the same form (isomorphism),
(2) A compound may exist in several forms (polymorphism),
(3) Similar radicles may partially replace each other without altering the form (isomorphous mixture),

rests the whole structure of modern mineralogical classification, and it is only by their aid that order has been introduced into systematic mineralogy; minerals were previously classified either by their form or their composition, and the two classifications did not lead to the same result.

The following remark of Fuchs relating to the alums is an early indication of the feeling that substances closely related in other respects must possess also a close chemical relationship.

"Sulphate of alumina forms, with ammonium, an alum just as well as with potash or with both these alkalies. Is it convenient to treat as three separate salts these three compounds, which do not differ at all in their physical properties? The potash can here be completely or partially replaced by ammonium, and *vice versâ*."

In accordance with this principle, minerals of apparently diverse composition, such as almandine and uvarovite, or potash alum and ammonia alum, could now be classified together if they possessed nearly the same crystalline form, and contained vicarious elements, even though they might have not a single constituent in common. The new views received immediate and rapid support from chemical analyses which showed that many minerals of the same form are also similar in composition.

The doctrine that a substance having a definite composition could crystallise in more than one form, or that two substances of different compositions could crystallise in the same form, appeared to destroy all that was exact in the science of mineralogy, which Haüy had so successfully erected upon a crystallographical basis, and many attempts were made to overthrow the new ideas.

Haüy had laid down the principle that every substance of definite chemical composition must possess a definite and characteristic crystalline form. If this principle appeared to be violated it could only be by some delusive contradiction in which the mineral appeared to possess a form that was not really its own. Thus in the neighbourhood of Paris were found rough crystals (known as "Fontainebleau sandstone") having the form of calcite, which, on analysis, proved to consist of sand grains up to the extent of 90 per cent. Here the crystalline form was due, not to the sand, but to the 10 per cent of calcite which it contains. The calcite, it was urged, possesses so powerful a crystallising action that it can impress its own characteristic form upon the sand.

Similarly, it was argued, celestite, $SrSO_4$, has the same form as barytes, $BaSO_4$, not by reason of its own composition, but on account of the small proportion of barium sulphate which it contains; the latter being supposed to have a much stronger crystallising power than the strontium sulphate. This explanation was subsequently abandoned, for even absolutely pure specimens of the two minerals possess what appears to be the same form; and the principle of the mutual replacement of vicarious constituents became firmly established.

More accurate measurements soon showed that two isomorphous substances have not in reality precisely the same form, as was at first supposed; on the contrary (except in the cubic system), the angles of two isomorphous substances are never precisely identical.

2. **Mineral Groups.**—Bearing the above principles in mind we may now see how they enable us to bring together by *chemical* relationships minerals which, on account of their similarity of appearance and physical properties, constitute a natural group, and which would have been brought together in any case under the Natural History System without regard to their composition.

The anhydrous carbonates of the allied elements calcium, magnesium, iron, zinc, and manganese all crystallise in the rhombohedral system, and their crystals have *nearly* the same angles; thus

Calcite . . .	$CaCO_3$	Rhombohedron angle	74° 55′
Magnesite . .	$MgCO_3$	,, ,,	72° 36′
Chalybite . .	$FeCO_3$	,, ,,	73° 0′
Calamine . .	$ZnCO_3$	,, ,,	72° 20′
Rhodochrosite .	$MnCO_3$	,, ,,	72° 58′

Further, they all have a perfect cleavage parallel to the faces of this rhombohedron.

In a "mineral group" such as this, which consists of similar compounds crystallising in nearly identical rhombohedra, it is evident that

whatever the relation between the crystalline form and chemical composition may be, it must be the same for each member of the group.

In the above series, which is known as that of the "rhombohedral carbonates," the similarity of composition consists in the fact that all the minerals have the same acid radicle and only differ in the metal with which it is combined; and further, that these metals possess the same valency. It is also possible that the five metals have themselves similar crystalline forms, for this is certainly the case in several other well-established "isomorphous groups."

The following group, for example, is one in which the metallic elements themselves have similar forms, or are isomorphous :—

Stibnite . .	Sb_2S_3	Orthorhombic	$a : b : c = 0{\cdot}993 : 1 : 1{\cdot}018$
Bismuthite . .	Bi_2S_3	,,	,, $= 0{\cdot}968 : 1 : 0{\cdot}985$
Orpiment . .	As_2S_3	,,	,, $= 0{\cdot}924 : 1 : 1{\cdot}052$

for the metals antimony, bismuth, and arsenic all crystallise in the rhombohedral system and have nearly the same angle—

Antimony	Rhombohedron angle	87° 7′
Bismuth	,, ,,	87° 40′
Arsenic	,, ,,	85° 4′

In this group of sulphides, therefore, the similarity of composition consists in the fact that the minerals contain the same element, sulphur, combined with the same number of atoms of equivalent metals which are themselves isomorphous with each other.

Or, in the language of Fuchs, the relation may be expressed in another way. In a mineral group one element (or radicle) is capable of replacing, partially or entirely, another element (or radicle) without introducing any considerable change in the crystalline form. The elements or radicles which are capable of this mutual replacement are often called isomorphous even when nothing is known of their own crystalline form.

That this replacement may take place either among the bases or in the acid radicle is apparent from the following instances :—

Barytes, $BaSO_4$ . .	Orthorhombic	$a : b : c = 0{\cdot}8152 : 1 : 1{\cdot}3136$
Celestite, $SrSO_4$ . .	,,	,, $= 0{\cdot}7789 : 1 : 1{\cdot}2800$
Anglesite, $PbSO_4$ . .	,,	,, $= 0{\cdot}7852 : 1 : 1{\cdot}2894$
Scheelite, $CaWO_4$	Tetragonal	$a : c = 1 : 1{\cdot}537$
Stolzite, $PbWO_4$	,,	,, $= 1 : 1{\cdot}567$
Wulfenite, $PbMoO_4$	,,	,, $= 1 : 1{\cdot}574$
Erythrite, $Co_3(AsO_4)_2 + 8H_2O$	Monoclinic	$a : b : c = 0{\cdot}7937 : 1 : 0{\cdot}7356$, $\beta = 74° 51′$
Vivianite, $Fe_3(PO_4)_2 + 8H_2O$	,,	,, $= 0{\cdot}7489 : 1 : 0{\cdot}7017$, $\beta = 75° 34′$

A comparison of wulfenite with scheelite, or of vivianite with erythrite shows that the replacement may take place simultaneously in the basic and the acid radicle.

In a mineral group there is always some difference in the form, that is to say in the angles, of the various members of the series, except when they belong to the cubic system; in the latter case they must be absolutely identical in form, since the corresponding forms of all cubic crystals have the same angles whatever their composition; as examples of mineral isomorphism in the cubic system we have salt, NaCl; sylvite, KCl; sal-ammoniac, NH_4Cl; cerargyrite, AgCl; bromargyrite, AgBr.

From this series we also learn that the isomorphous replacement may be not only atom by atom of equivalent elements, as between salt and sylvite, but that a polyatomic radicle may replace another radicle or element of the same valency; in sal-ammoniac as compared with salt, the univalent *radicle* ammonium has replaced the univalent *element* sodium.

In a similar way it is generally supposed that two univalent atoms or radicles may replace one divalent atom or radicle; three divalent atoms may replace two trivalent atoms, and so on. Thus chrysoberyl, $BeAl_2O_4$, is said to be isomorphous with diaspore, $H_2Al_2O_4$, and phenakite, Be_2SiO_4, with dioptase, H_2CuSiO_4. In the first instance, two univalent atoms of hydrogen replace one divalent atom of beryllium; in the second instance, the tetravalent group Be_2 is replaced by the tetravalent group H_2Cu. In reality the evidence of such direct replacement of one atom by two or more atoms in isomorphous compounds is far from satisfactory. It is doubtful whether unequal numbers of atoms can so replace one another except when united as radicles of the same valency.

The chief groups of vicarious elements and radicles among minerals are—

H, K, Rb, Cs, Na, Li, NH_4, in the haloids, nitrates, phosphates, and silicates.
F, Cl, Br, I, OH, in the haloids, phosphates, and silicates.
Au, Ag, Hg, Cu′, Tl, in the sulphides and sulpho-salts.
Be, Zn, Mg, Fe, Mn, Cu″, Ca, in the phosphates and silicates.
Mg, Zn, Fe, Mn, Ni, Co, in the sulphates.
Ca, Ba, Sr, Mg, Pb, Zn, Fe, Mn, in the carbonates and sulphates.
Fe, Ni, Co, Mn, Zn, Cd, in the sulphides and sulpho-salts.
Al, Fe‴, Cr, Mn‴, in the oxides, aluminates, phosphates, and silicates.
Si, Ti, Zr, Sn, Pb, in the oxides and silicates.
S, Se, Te, in the sulphides and sulpho-salts.
As, Sb, Bi, in the oxides, sulphides, and sulpho-salts.
P, V, As, in the phosphates, etc.
Mo, W, in the oxides and molybdates, etc.
Y, Er, Ce, La, Di, in the haloids, phosphates, silicates, etc.

3. **The Physical Relations of Minerals belonging to the same Group.**—Isomorphous minerals really differ in their physical properties as well as in their form and composition. Even when an isomorphous group belongs to the cubic system so that its members cannot be distinguished by their angles, they possess different physical characters according to

their composition. Thus potassium-alum, $KAl(SO_4)_2 . 12H_2O$, and chrome-alum, $KCr(SO_4)_2 . 12H_2O$, differ in their general characters such as specific gravity.

	Spec. Grav.
Potassium-alum	1·735
Chromium-alum	1·817

They can also be distinguished by their crystallophysical characters, both those which in the cubic system differ for different directions, *e.g.* the elasticity, and those which, like the refractive index or the thermal conductivity, are the same for all directions.

In the matter of elasticity, if P denote the weight in kilograms theoretically sufficient to extend a rod whose section is a square millimeter, cut out of a crystal parallel to a cubic axis, to double its length, and if Q denote the weight required for a similar section cut parallel to a cube diagonal, we have—

	P.	Q.	Refractive Index.
Potassium-alum . .	1806	2058	1·4557
Chromium-alum . .	1608	1832	1·481

Thus if account be taken of *all* their properties, there is no risk of confusing different substances which have the same angles, even in the cubic system.

When the isomorphous substances belong to some other system they differ, of course, still more conspicuously in physical characters, since their double refraction is not the same.

Similarly with polymorphous substances, not only do they differ in their angles, and in the crystallophysical characters which might naturally be expected to depend on the crystalline form, but also in their general physical characters. Iron pyrites and marcasite have the same empirical formula, FeS_2, but the two minerals differ in specific heat and specific gravity.

	Spec. Grav.	Spec. Heat.
Iron pyrites . . .	5·03	0·1306
Marcasite . . .	4·88	0·1332

Generally speaking, the cleavages are parallel to the same forms in all the members of an isomorphous group; but they may differ in facility; thus anglesite, $PbSO_4$, possesses the same cleavages—prism {110} and basal pinakoid {001}—as barytes, $BaSO_4$, and celestite, $SrSO_4$, but they are by no means so perfect in anglesite.

The principal refractive indices may not only differ in their absolute magnitudes, but also in their ratios, and where it is possible (in the monoclinic and anorthic systems), the axes of the indicatrix may occupy different positions. Thus of the tetragonal salts, $CaS_2O_6 . 4H_2O$, $SrS_2O_6 . 4H_2O$, and $PbS_2O_6 . 4H_2O$, the first two are negative and the third is positive.

Again, in all the members of the orthorhombic aragonite group the acute bisectrix is perpendicular to the basal plane (001) and the birefring-

ence is negative, but the axial plane is parallel to the macro-pinakoid (100) in aragonite, $CaCO_3$, and strontianite, $SrCO_3$, but to the brachy-pinakoid (010) in witherite, $BaCO_3$, and cerussite, $PbCO_3$.

In the monoclinic pyroxene group the plane of the optic axes is always the clino-pinakoid (010), but the extinction angle on this face, *i.e.* the inclination of the acute bisectrix to the vertical axis, is as follows :—

Acmite . .	$NaFe(SiO_3)_2$ . .	$+ 5\frac{1}{2}^\circ$
Spodumene . .	$LiAl(SiO_3)_2$ . .	$+ 26^\circ$
Diopside . .	$CaMg(SiO_3)_2$ . .	$+ 36^\circ$
Hedenbergite .	$CaFe(SiO_3)_2$ . .	$+ 48^\circ$

On the other hand, there are numerous instances in which the optical characters of the members of an isomorphous group, though different, are closely related. In the barytes group, for example, all three minerals are positive, have the acute bisectrix perpendicular to (100), and have the plane of the optic axes parallel to (001).

It may happen that two isomorphous compounds, or the two forms of a dimorphous compound, appear to be identical in some one physical property, at least so far as present experimental methods are able to determine it, but they cannot be identical in all their physical properties.

Thus calcite ($CaCO_3$—rhombohedral) and aragonite ($CaCO_3$—orthorhombic) have nearly the same specific heat, 0·2036, but they differ in specific gravity ; calcite = 2·713, aragonite = 2·93.

The two modifications of sulphur have nearly the same specific gravity, but differ in their specific heat, that of the monoclinic variety being the higher.

The first instances are sufficient to indicate that with every change of composition the physical properties are also changed, and a consideration of all such cases renders it highly probable that the physical properties of any compound could be deduced from those of its constituents if we knew how these constituents are united and arranged ; but the last instance calls to mind the inadequacy of present knowledge concerning the chemical composition of even the simplest crystallised substances, for it is as yet impossible to explain wherein consists the difference between even orthorhombic and monoclinic sulphur.

Among organic compounds a study of many series of derivatives enables us to distinguish between two sorts of polymorphous compounds, those in which the difference probably consists in the various arrangements of the same atoms within the molecule (chemical isomerism), and those in which it consists in a multiplication of the atoms within the molecule (chemical polymerism).

In mineralogy such distinctions have no meaning in the present state of our knowledge, and it is impossible, from the number and nature of the elements in a crystallised mineral, to predict either its crystalline form or its physical properties.

But the problem is very different if our attention be confined to a set of minerals in which there is reason to believe that the constituent

atoms are related to each other in precisely the same way in the various members of the series.

This is certainly the case in a series of isomorphous compounds, in which the influence of the different vicarious constituents may be directly compared. Here, without knowing what is the exact relation between the properties of the compound and those of its constituents, we may confidently assert that the relation is the same for all the members of the series, and may even predict the properties of some as yet unknown compound belonging to it.

For example, potassium, rubidium, and cæsium are three monovalent elements occupying consecutive positions in the even series of Mendeléef's table (p. 199), *i.e.* three elements giving rise to eutropic compounds, and they act as vicarious constituents in a number of isomorphous salts; as regards its atomic weight, rubidium lies between potassium and cæsium. Tutton has compared the simple sulphates of these metals, K_2SO_4, Rb_2SO_4, and Cs_2SO_4, and has shown that both as regards crystalline form, specific gravity, thermal expansion, and corresponding refractive indices, the rubidium salt lies between the potassium and cæsium salts.

The same is true of the rubidium as compared with the potassium and cæsium compounds in twenty-two double sulphates studied by the same observer; these belong to the series whose formula is $R'_2SO_4 . R''SO_4 . 6H_2O$, where R′ may be K, Rb, or Cs, and R″ may be Mg, Zn, Fe, Ni, Co, Cu. For each triad of salts in which R″ is the same divalent metal, the properties of the rubidium salt are intermediate between those of the potassium and the cæsium salts.

There can be little doubt that in an isomorphous series of eutropic compounds such as this, the properties of the salts are similar functions of the atomic weights of the elements. It is certain also that the properties of the elements themselves are periodic functions of their atomic weights, and therefore that in an isomorphous series the properties of each member can be deduced in one and the same way from the properties of its constituents. Thus the K-Mn compound and the K-Cd compound belonging to the above series of double sulphates have not yet been prepared, but their crystalline form, specific gravity, and refractive indices can be predicted on the assumption that K, Mn, and Cd will play the same part in them as in the known compounds.

Ca, Sr, Ba are another set of elements giving rise to eutropic compounds which behave in the same way, so that in any isomorphous series of salts of these three elements the physical properties of the strontium salt are intermediate between the corresponding properties of the calcium and barium salts.

Among minerals, few series are known which are eutropic. The members of a mineral group are often corresponding compounds of elements which are somewhat closely related, but not so closely as are K, Rb, and Cs.

Nevertheless, a large number of minerals do naturally fall into groups like the calcite group, in which similarity of crystalline form is evidently

accompanied by similarity of composition, and also by similarity of physical properties, in the sense that as one constituent is replaced by another, corresponding changes are introduced into the physical properties.

In these, however, it is by no means certain at present that all the corresponding numbers follow in general the same order as the atomic weights of the vicarious constituents. In the aragonite group we have

	a : b : c.	Sp. Gr.	Refr. Index.	Sp. Heat.
Aragonite, $CaCO_3$(Ca = 40)	0·6228 : 1 : 0·7207	2·95	$\gamma = 1·6859$	0·2036
Strontianite, $SrCO_3$(Sr = 87)	0·6089 : 1 : 0·7237	3·70	$\gamma = 1·6670$	0·1445
Witherite, $BaCO_3$(Ba = 137)	0·5949 : 1 : 0·7413	4·30	$\beta = 1·6760$	0·1096
Cerussite, $PbCO_3$(Pb = 207)	0·6220 : 1 : 0·7168	6·50	$\beta = 2·0763$	0·1086

The refractive indices which are compared in the above table are those which belong to the axis *b*; in aragonite and strontianite this axis is the obtuse bisectrix (γ), in the other two minerals it is perpendicular to the plane of the optic axes (β). Neither in the aragonite group nor in the barytes group quoted above do the axial ratios follow in the order of the atomic weights of the vicarious constituents, except so far as the eutropic elements Ca, Sr, Ba are concerned. The element Pb introduces a sudden change in the series; its compounds are isomorphous, but not eutropic, with those of Ca, Sr, Ba.

Thus a mineral group may exhibit similarity of form, composition, and other properties without possessing a regular sequence of properties in the order of the atomic weights of the replacing elements; or, in other words, a mineral group may be isomorphous without being a "eutropic" series.

Sometimes the change produced by the replacement of one radicle by another is so great that the two compounds can scarcely be called isomorphous in the strict sense. They may not only differ considerably in angles but even in symmetry; they may belong to different classes within the same system, or they may even belong to different systems, while preserving an obvious similarity in angles.

Thus calcite, $CaCO_3$, possesses an axis of alternating *dihexagonal* symmetry; dolomite, $CaCO_3 . MgCO_3$, crystallises in almost the same rhombohedra and has the same cleavage, but though its angles are so close to those of calcite, its symmetry is different, and it possesses an axis of alternating *hexagonal* symmetry. It is true that dolomite may differ chemically from calcite in being a double salt. But the close relationship between the two minerals, both in physical and chemical properties, compels us to refer dolomite to the calcite group without any hesitation.

Again, albite, $NaAlSi_3O_8$, and orthoclase, $KAlSi_3O_8$, must be referred together to the felspar group on account of their intimate relations, in spite of the fact that albite is anorthic, and orthoclase to all appearance monoclinic.

Some authors wish to reserve the term "isomorphous" exclusively for those compounds in which the relationships are absolutely uniform, as in the sulphates of potassium, rubidium, and cæsium.

Hence the term "mineral group" is used in this book for what are

sometimes called "isomorphous" groups, and it must be understood to mean a group of minerals which possess both a close similarity of composition and of crystalline form, whether they be eutropic or not, and whether their symmetry be the same or not.

The particular change in crystalline form produced by replacing one element or radicle by another, whether the resulting compounds are isomorphous or not, is sometimes (after Groth) termed the "morphotropic" action of the element or radicle, *e.g.* the contraction of the *a*-axis produced by substituting Sr for Ca in the aragonite group; it depends not only upon the nature of the replacing constituent, but also upon that of the constituents which are common to the two compounds.

In a series of organic compounds where a number of replacements can be effected, and where it is known exactly what are the replacing radicles, and how they are related to the remaining constituents, the morphotropic action of a radicle may sometimes be very clearly traced. Thus in some derivatives of benzene it was pointed out by Groth that the replacement of H by OH alters in particular one axial ratio without changing the symmetry, whereas the replacement of H by Cl or Br changes the system of the crystal.

A very striking instance of morphotropy is afforded by the three minerals of the monoclinic chondrodite group, in which, as established by Penfield and Howe, the addition of the molecule Mg_2SiO_4 adds a certain length to the vertical axis without affecting the other axes or the axial angle ($\beta = 90°$); the increase for each such molecule is $\frac{2}{9}$ of the vertical axis of clinohumite.

		a	*b*	*c*
Chondrodite . .	$Mg_3[Mg(F.OH)]_2[SiO_4]_2$	1·0863	: 1 :	5 × 0·6290
Humite . . .	$Mg_5[Mg(F.OH)]_2[SiO_4]_3$	1·0802	: 1 :	7 × 0·6290
Clinohumite . .	$Mg_7[Mg(F.OH)]_2[SiO_4]_4$	1·0803	: 1 :	9 × 0·6288

Among minerals it is not yet possible to trace many such consistent changes, but the whole question opens an interesting inquiry whether there may not be morphotropic relations between minerals which are not chemically related in the ordinary sense.

Thus the two minerals, zincite, ZnO, and greenockite, CdS, belong to the distinct chemical groups of oxides and sulphides, and can scarcely be called isomorphous. But their composition is similar in the sense that oxygen is replaced by sulphur and cadmium by zinc, and in form they are almost identical, since zincite belongs to the greenockite class of crystals and has almost the same angles as greenockite. Wurtzite, ZnS, is isomorphous with greenockite and is a connecting link between zincite and greenockite.

Such relations are by no means rare. Other oxides are found to be very similar in form to the corresponding sulphides; for example, the orthorhombic oxide valentinite, Sb_2O_3, to the orthorhombic sulphide stibnite, Sb_2S_3.

Before pursuing further, however, the differences which exist between what are confessedly different minerals, it will be necessary to consider the

differences which exist between various specimens belonging to the same mineral group.

4. **The Variations in the Composition of a Mineral.**—When minerals of somewhat complex constitution are analysed, it is found very difficult to assign a definite formula even to the most perfect and homogeneous crystals, not only on account of the large number of elements which they contain, but also because the proportions of those elements appear to vary in an erratic manner and never exactly to obey the law of definite combining proportions.

Thus the garnets constitute a very sharply defined mineral group. They crystallise extremely well, almost always in rhombic dodecahedra. They resemble each other very closely, and cannot well be confused with any other mineral, in spite of their own differences in colour and in chemical composition.

The following are actual analyses of garnets:—

I. A lime-alumina garnet (grossular) from Monzoni.
II. An iron-alumina garnet (almandine) from Fahlun.
III. A lime-iron garnet (melanite) from Långban.
IV. A lime-chrome garnet (uvarovite) from the Urals.

	I.	II.	III.	IV.
SiO_2	39·53	39·66	35·10	35·57
Al_2O_3	20·15	19·66	...	6·25
Fe_2O_3	4·94	...	29·10	
Cr_2O_3	...	...	...	23·45
CaO	33·88	...	26·91	33·22
MnO	...	1·80	7·08	...
FeO	...	39·68	...	...
MgO	1·72	...	...	...
	100·22	100·80	98·19	98·49

With these we may compare the theoretical compositions of the following four compounds which might be expected to be isomorphous:—

	$Ca_3Al_2(SiO_4)_3$	$Fe_3Al_2(SiO_4)_3$	$Ca_3Fe_2(SiO_4)_3$	$Ca_3Cr_2(SiO_4)_3$
SiO_2	40·01	36·15	35·45	38·23
Al_2O_3	22·69	20·51	...	...
Fe_2O_3	...	...	31·49	...
Cr_2O_3	...	...	...	32·50
CaO	37·30	...	33·06	29·27
FeO	...	43·34	...	...

Now these minerals, though they differ so considerably in composition, belong without doubt to the same group and are even more closely related in their physical characters than the members of many other mineral groups, such as that of the rhombohedral carbonates given above.

But each mineral, while it approximates more or less to the law of definite combining proportions, as represented by the formula in the second table, differs considerably therefrom.

The differences are clearly in accordance with the principle of vicarious constituents stated above. In the first analysis the alumina is too low, but some ferric oxide is present to account for the deficiency. In the second analysis some of the ferrous oxide is replaced by a proportion of MnO. If, however, the law of definite combining proportions, upon which chemistry appears to be based, is to hold true, how are these replacing constituents present, and what determines their proportions?

A large number of mineral analyses are vitiated by the enclosure of one mineral in another. Transparent minerals, even when in the most perfect crystals, are usually found, when examined by the microscope, to be full of minute enclosed crystals of other compounds which have to be removed by picking, or by the use of heavy solutions, before a trustworthy analysis can be made. Analysis III., for example, yielded also 0·98 of K_2O, which is probably present as a constituent of some enclosed mineral and does not belong to the garnet itself. But even when all these precautions have been taken, the most homogeneous garnets will give very variable proportions for their vicarious constituents.

If the crystals were liquids it would be natural to suggest that they were mixtures in which the constituents are able to mingle in various proportions, like alcohol and water. Analyses of such mixtures might lead to the most various proportions, but they would always be expressible as a certain amount of alcohol mixed with a certain amount of water. If the liquids were perfectly miscible the mixture would be quite homogeneous, but the atomic ratios would not be definite.

This is, in fact, now known to be the real explanation of the difficulty. It has been established that certain compounds are perfectly miscible in the solid state, exactly as certain substances, like alcohol and water, are miscible in the liquid state, and that they mix to form perfect *crystals*, which are as homogeneous as those of a single definite compound.

By mixing the solutions of two or more such compounds in various proportions, and allowing them to crystallise, the laws of these homogeneous mixtures have been studied and are now fairly well known. They resemble so completely the laws which govern solutions themselves and their mixtures, that such homogeneous mixed crystals are very generally known as "solid solutions."

Now the substances which can mix to form solid solutions are precisely the isomorphous compounds, not only such as are eutropic, but also those which are isomorphous in the more general sense. Long before the nature and properties of crystallised mixtures were studied, Mitscherlich, in the course of his researches on isomorphism, made the great discovery that *isomorphous compounds are capable of mixing in varying proportions to form homogeneous crystals.*

The principle of vicarious constituents stated by Fuchs may be regarded as another way of stating the same fact. This remarkable property has been so completely established by the study of those compounds, which, like the sulphates of potassium, rubidium, and cæsium, are uniformly related in composition and form, that many authors restrict

the term "isomorphous" to substances which are similar in composition and form, *and possess the property of forming homogeneous mixed crystals or "isomorphous mixtures."* For this reason, again, we have preferred to use the term "Mineral Group" for what is sometimes called an isomorphous series of minerals, since there is not always evidence that all the members of the series can crystallise together as mixtures.

5. **Isomorphous Mixtures.**—Most of the difficulties encountered in interpreting the variable constitution of a mineral find a satisfactory explanation in Mitscherlich's great principle.

Isomorphous mixtures are especially common in the mineral kingdom, since minerals have rarely been formed as pure isolated compounds, but have generally separated from miscellaneous materials, among which they have been free to mix with isomorphous substances.

The nature of such mixtures can be very easily studied by laboratory experiments upon soluble salts. Thus, if A and B be two substances which are isomorphous in the most rigid sense, like $ZnSO_4 . 7H_2O$ and $MgSO_4 . 7H_2O$, which are similar in composition and nearly identical in form, they are capable of forming crystals *of nearly the same form as their own*, whose chemical composition may be represented as $mA + nB$.

Thus crystals may be made which are hydrated sulphates containing both zinc and magnesium, and having a form whose angles are near those of each of these sulphates. Such crystals can neither be called zinc sulphate nor magnesium sulphate, yet their composition is such that they can always be expressed as a mixture of a certain amount of one with a certain amount of the other: $m(ZnSO_4 . 7H_2O) + n(MgSO_4 . 7H_2O)$; they are said to be an "isomorphous mixture" of the zinc and magnesium sulphates. Now the ferrous sulphate $FeSO_4 . 7H_2O$, which is a member of the same isomorphous group, may also enter into such an isomorphous mixture, and accordingly it is found that similar crystals of the hydrated sulphate containing zinc, magnesium and iron, have the proportions of their constituents so related that the composition may be expressed as $x(ZnSO_4 . 7H_2O) + y(MgSO_4 . 7H_2O) + z(FeSO_4 . 7H_2O)$, or are isomorphous mixtures of the three sulphates; x, y, and z being different for different specimens.

Any mineral, therefore, in crystallising is capable of "dissolving" certain quantities of one or more substances isomorphous with itself and of solidifying in homogeneous crystals. Very few minerals are absolutely simple; most, when carefully analysed, are found to contain small quantities of what were at first regarded as impurities, but are now known to be intermixtures of isomorphous substances.

Thus zinc-blende, ZnS, generally contains a certain percentage of iron —this, however, is present as FeS, and not as metallic iron or as any other compound of iron, for the formula of blende may always be expressed as $xZnS + yFeS$, the percentage of sulphur being always exactly sufficient to be combined in the ratio of one atom to one atom with the amounts of zinc and iron present.

Now, in some cases, the compounds of which the mineral is a mixture are known to exist independently as separate minerals; in other cases

one or more of these compounds, though not known to exist independently, may be produced artificially; the cubic compound FeS which enters into the composition of most blende does not occur at all as a terrestrial mineral, but it may be the substance found in some meteorites, and known by the name of troilite; FeS has also been prepared artificially in crystals belonging to the cubic system.

So many cases have now been established by the discovery or preparation of the missing isomorphous constituents, that even when the separate components have not yet been prepared independently a mineral is still regarded as a mixture of certain isomorphous compounds, one or more of which may be hypothetical.

Thus, if it is found that a mineral of exceedingly variable composition may always be expressed as $x\mathrm{A} + y\mathrm{B} + z\mathrm{C}$, where A and B are known as independent compounds, but C is merely hypothetical, the mineral is regarded as an isomorphous mixture of A, B, and C, although there is nothing to prove the existence of C as a compound isomorphous with A and B except its presence in the mixed crystals.

Garnets which contain any or all of the elements calcium, aluminium, chromium and iron (ferrous and ferric) may always be regarded as isomorphous mixtures of the following compounds:—

(1) $Ca_3Al_2(SiO_4)_3$	(3) $Ca_3Fe_2(SiO_4)_3$	(5) $Ca_3Cr_2(SiO_4)_3$
(2) $Fe_3Al_2(SiO_4)_3$	(4) $Fe_3Fe_2(SiO_4)_3$	(6) $Fe_3Cr_2(SiO_4)_3$

In other words calcium and dyad iron are vicarious elements which may replace each other in the garnets, while aluminium, triad iron and chromium are also vicarious in this group.

In the analyses given on p. 223

I. may be expressed approximately as

$$73Ca_3Al_2(SiO_4)_3 + 13Ca_3Fe_2(SiO_4)_3 + 6Mg_3Al_2(SiO_4)_3,$$

II. as

$$57Fe_3Al_2(SiO_4)_3 + 2Mn_3Al_2(SiO_4)_3,$$

III. as

$$5Ca_3Fe_2(SiO_4)_3 + Mn_3Fe_2(SiO_4)_3,$$

IV. as

$$50Ca_3Cr_2(SiO_4)_3 + 23Ca_3Al_2(SiO_4)_3.$$

In I. a certain amount of CaO is replaced by MgO.
In II. a certain amount of FeO is replaced by MnO.
In III. a certain amount of CaO is replaced by MnO.
In IV. a certain amount of Cr_2O_3 is replaced by Al_2O_3.

Hence, in addition to the six orthosilicates given above, we have also to suppose that the following may enter equally well into the composition of a garnet:—

(7) $Mg_3Al_2(SiO_4)_3$	(9) $Mg_3Fe_2(SiO_4)_3$	(11) $Mg_3Cr_2(SiO_4)_3$
(8) $Mn_3Al_2(SiO_4)_3$	(10) $Mn_3Fe_2(SiO_4)_3$	(12) $Mn_3Cr_2(SiO_4)_3$

and although none of these silicates is known in a state of absolute purity they are compounds which would be expected to be isomorphous, and they suffice to explain all the variations in the composition of the garnet.

For the sake of abbreviation the intermixture of isomorphous minerals may be regarded as a mutual replacement of vicarious elements, and may be so indicated in the formula. Thus, the anhydrous rhombohedral carbonate known by the name of ankerite contains both calcium and iron with magnesium and manganese; and since these elements are present in varying proportions the formula of the mineral may conveniently be written (Ca, Fe, Mg, Mn)CO_3—or RCO_3 (R = Ca, Fe, Mg, Mn)—where the elements in the bracket are supposed to be capable of replacing each other in variable proportions; that is to say, a certain amount of the Ca may be replaced by the equivalent weight of Fe, and so on.

Similarly the minerals of the garnet group may be represented by the "general formula" $R''_3R'''_2(SiO_4)_3$; (R'' = Ca, Mg, Fe, Mn) (R''' = Al, Fe, Cr): a formula which shows that, whatever its composition, a garnet may be regarded as an orthosilicate of three atoms of a divalent and two atoms of a trivalent metal.

6. **Mixtures of Dimorphous Substances.**—It sometimes happens that a well-defined mineral is obviously, so far as its composition is concerned, to be regarded as a mixture in varying proportions of two compounds A and B; further, that A and B are known to occur as minerals or may be prepared artificially, but have totally distinct forms.

The mineral cannot, then, it might be urged, be regarded as a mixture of two isomorphous substances, since A and B, though they are of similar composition, crystallise in different forms. For example, a variety of rhombohedral calcite from Leadhills in Lanarkshire contains a variable proportion of lead carbonate, and is for this reason distinguished by the name of plumbocalcite; it must be regarded as an isomorphous mixture of $CaCO_3$ and $PbCO_3$, since its composition may always be expressed as $mCaCO_3 + nPbCO_3$. Now $PbCO_3$ is only known to occur in nature in orthorhombic crystals as the mineral cerussite.

How, then, can this enter into an *isomorphous* mixture with calcite? The answer to this question is supplied by two other minerals, namely, aragonite and tarnowitzite. Aragonite has the same composition, $CaCO_3$, as calcite, but is orthorhombic. Tarnowitzite is orthorhombic carbonate of lime $CaCO_3$, containing a variable amount of lead carbonate; it therefore bears the same relation to aragonite as plumbocalcite to calcite, and is to be regarded as an isomorphous mixture of aragonite and cerussite.

We have, then, the following relations—

	Rhombohedral.	Orthorhombic.
$CaCO_3$	Calcite	Aragonite
(Ca, Pb)CO_3	Plumbocalcite	Tarnowitzite
$PbCO_3$		Cerussite

Everything becomes clear if we suppose that $PbCO_3$ may exist in more than one crystalline form. Now two modifications are actually

known in the case of $CaCO_3$, which exists as calcite and aragonite; $PbCO_3$ as cerussite is isomorphous with the latter; it may therefore be expected to exist in a second modification isomorphous with the former, and this supposition is supported by the existence of such a mineral as plumbocalcite.

Calcium carbonate, then, is dimorphous, existing both as calcite and aragonite. $PbCO_3$ is dimorphous, existing as cerussite, and also (in plumbocalcite) as a rhombohedral substance capable of entering into an isomorphous mixture with calcite.

Sometimes crystals may be artificially produced which have the same composition as known minerals but a different form, thus proving the dimorphism of the mineral; and the form has frequently proved to be precisely that which was required to fill up a gap in some mineral group where its mixtures alone are known.

Of this the oxides of arsenic and antimony have generally been quoted as a typical example. Originally Sb_2O_3 was only known as the orthorhombic mineral valentinite, and As_2O_3 was only known as the cubic mineral arsenolite; the two substances are precisely similar in composition and might be expected to be isomorphous, but the difference in system and form appeared to negative the supposition.

In 1851, however, a cubic variety of Sb_2O_3 was discovered and named senarmontite; this is obviously to be regarded as isomorphous with arsenolite. Now if Sb_2O_3 is isomorphous with As_2O_3 in its cubic modification, it is probably so also in its orthorhombic modification: a consideration which led to the confident prediction of an orthorhombic form of As_2O_3. This prediction was confirmed by the discovery of artificial crystals of As_2O_3 belonging to the orthorhombic system, and having angles very near those of valentinite. Similar crystals have since been found in nature and are known as the mineral claudetite. (Subsequent investigation has shown that claudetite is really monoclinic, though very close in angles to the orthorhombic valentinite.) The two oxides are therefore not only isomorphous, but also "isodimorphous." In this instance the isodimorphism is proved by the actual existence of the four sorts of crystals; in the case of calcite and cerussite the isodimorphism is only indicated by the existence of isomorphous mixtures.

So far, the supposition that in two isodimorphous minerals mixtures only take place between the similar modifications may appear to be a pure assumption; no evidence has been adduced above to prove that cerussite only mixes with aragonite and not with calcite; this fact is really established by the more exact knowledge of the nature of solid solutions, derived from the study of mixtures artificially prepared in the laboratory, and especially by their physical properties.

7. **The Crystalline Form and Physical Properties of Solid Solutions.**—Firstly, as regards the form of a mixed crystal, it might be expected that the *angles* would be intermediate between those of its two constituents. This indeed appears to be the case in some instances; for example, the rhombohedral carbonate intermediate in composition between magnesite, $MgCO_3$, and chalybite, $FeCO_3$, received the name mesitite as

intermediate between these minerals; it has a rhombohedron angle 72° 46′, that of magnesite being 72 36′, and that of chalybite 73° 0′. But in other groups this is by no means always the case.

Among artificial compounds the only series of observations which has any pretensions to completeness is that of Dufet on the orthorhombic mixtures of $MgSO_4 . 7H_2O$ with $ZnSO_4 . 7H_2O$. The following table gives the results which he obtained for the two salts and seven mixtures:—

	Percentage of Mg.-salt	Spec. Grav.	110 : 110	010 : 111.
$MgSO_4 . 7H_2O$	100	1·6760	89° 25′	63° 40½′
	78·88	1·7359	89° 17½′	63° 43′
	74·44	1·7472	89° 15′	63° 44½′
	62·70	1·7816	89° 11′	63° 46¾′
	57·59	1·7977	89° 8′	63° 46½′
	42·80	1·8415	89° 3½′	63° 49′
	35·64	1·8604	89° 1′	63° 48½′
	18·11	1·9094	88° 54′	63° 53′
$ZnSO_4 . 7H_2O$	0	1·9600	88° 48′	63° 53′

Here it will be noticed that the differences of angle are so slight that not much reliance can be placed upon them; they are scarcely beyond the limit of experimental errors.

When, however, we pass to the physical properties, we find from the second column that the specific gravity varies in an unmistakable and a very regular manner; in this respect the mixed crystals behave as though they were a mere mechanical mixture of the two constituent salts. Now this is found to be equally true of all isomorphous mixtures which have been investigated; the specific gravity varies regularly with the composition of the mixture.

Those crystallised mixtures in which all the physical properties are continuous functions of the composition may now be distinguished as "solid solutions"; though crystals, they behave in this respect like mechanical mixtures or like many mixed liquids.

By means of heavy liquids, as described on p. 191, it is easy to determine the specific gravity of very small crystals with accuracy, and the densities of many such mixtures have been measured. The volume occupied by a given weight of a substance is inversely proportional to its density; in Fig. 374 the specific volume $\left(= \frac{1}{\text{spec. grav.}} \right)$ is compared with the percentage composition of the mixture.

The diagram represents the relation between specific volume and composition in mixed crystals of potassium sulphate and ammonium sulphate; the ordinate being taken proportional to the specific volume, and the abscissa to the percentage of ammonium sulphate in the mixed crystals examined; we have—

For K_2SO_4	spec. grav. = 2·666	spec. vol. = 0·3751 (A)
„ $(NH_4)_2SO_4$	„ „ 1·774	„ „ 0·5636 (B)

Then it is found that the point corresponding to any mixed crystal lies on the straight line AB, and, consequently, if the composition be known the specific volume may be predicted, and *vice versâ*.

Thus a mixed crystal containing 20·5 per cent of $(NH_4)_2SO_4$ will have the specific volume 0·4138, and therefore the specific gravity 2·417.

In this case the two salts are capable of crystallising together in all proportions; sometimes each of two isomorphous compounds can dissolve only small proportions of the other, while mixtures in anything like equal proportions will not crystallise, at least under ordinary conditions. Such mixtures may be regarded as *dilute* solutions of the one substance in the other.

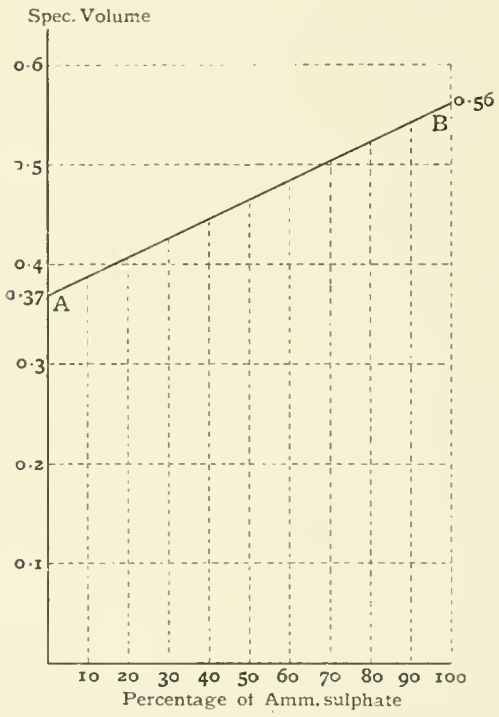

Fig. 374.—Mixture of Potassium and Ammonium Sulphates.

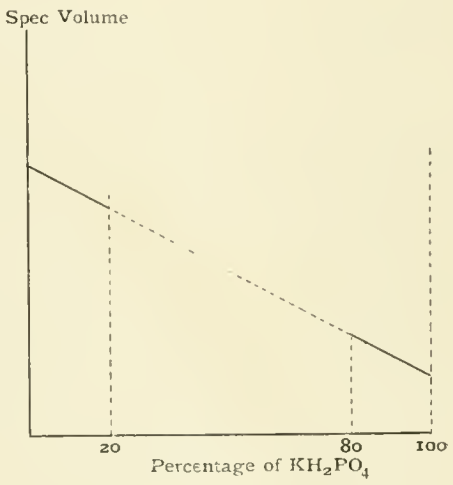

Fig. 375.—Mixture of Potassium and Ammonium Phosphates.

Thus acid ammonium phosphate $(NH_4)H_2PO_4$ will dissolve varying proportions up to 20 per cent of the corresponding potassium salt KH_2PO_4; and, similarly, the potassium salt will dissolve up to 20 per cent of the ammonium salt, but intermediate mixtures refuse to form homogeneous crystals.

This state of things is represented by Fig. 375, where the line is interrupted, but here also the one part is a continuation of the other, showing that the mixture is as regular as in the preceding case.

There are two remarkable classes of compounds in which this continuity is broken: (1) isodimorphous substances, and (2) substances which not only form isomorphous mixtures but also double salts.

(1) *Mixtures of Isodimorphous Substances.*—The salt $MgSO_4 . 7H_2O$ (sp. gr. = 1·677, sp. vol. = 0·596) will dissolve $FeSO_4 . 7H_2O$ up to 19 per

cent; and $FeSO_4 . 7H_2O$ (sp. gr. = 1·898, sp. vol. = 0·527) will dissolve $MgSO_4 . 7H_2O$ up to 54 per cent.

But when the corresponding diagram is made by plotting points for the different mixtures, it is found that they lie not upon one line but upon two lines (Fig. 376). The lower line indicates that the sulphate of iron is mixing with a substance whose specific volume is 0·591 (sp. gr. = 1·691), not 0·596, and the upper line indicates that the sulphate of magnesium is mixing with a substance whose specific volume is 0·533 (sp. gr. = 1·875), not 0·527.

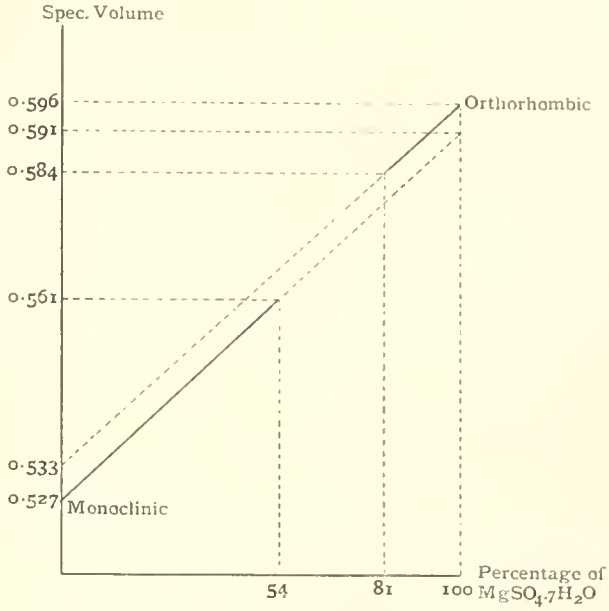

Fig. 376. Mixture of Iron and Magnesium Sulphates.

Now the pure salt $MgSO_4 . 7H_2O$ is orthorhombic, and the pure salt $FeSO_4 . 7H_2O$ is monoclinic; the mixed crystals represented by the upper line belong to the orthorhombic system, and those represented by the lower line to the monoclinic system.

We conclude that the unknown substance of specific gravity 1·691 which is dissolved by the ferrous sulphate is a monoclinic modification of magnesium sulphate, which is unstable under ordinary conditions, but capable of entering into mixtures with the isomorphous ferrous sulphate. Similarly, an unstable orthorhombic salt $FeSO_4 . 7H_2O$, of specific gravity 1·875, is isomorphous with ordinary $MgSO_4 . 7H_2O$. Both substances are therefore to be considered as dimorphous.

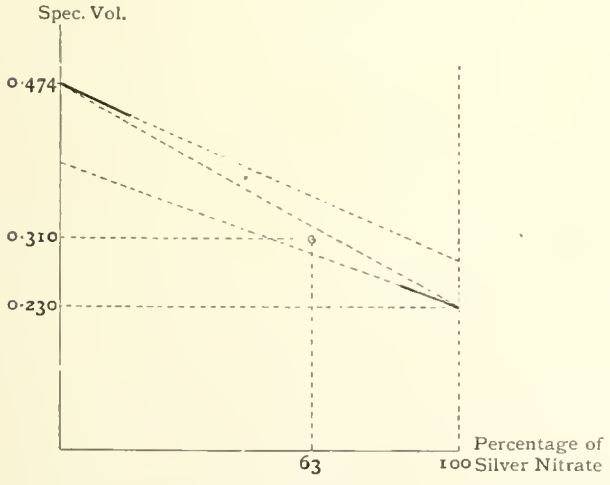

Fig. 377.—Mixture of Silver and Potassium Nitrates.

(2) *Double Salts.* — The nature of mixtures of the orthorhombic $AgNO_3$ and KNO_3 is shown in Fig. 377.

Each salt can dissolve a small quantity of an (unstable) modification of the other crystallising in the orthorhombic system; but they also crystallise together in *equal* molecular proportions to form a salt $KNO_3 . AgNO_3$, which is monoclinic and has the specific volume 0·310 (sp. gr. = 3·219) instead of 0·320 (sp. gr. = 3·116), which would be that of the isomor-

phous mixture containing 63 per cent $AgNO_3$ and represented by $(K,Ag)NO_3,[K:Ag = 1:1]$. The corresponding point on the diagram lies off the dotted lines representing isomorphous mixtures. It is usually found to be the case, where such compounds have been investigated, that in the formation of the double salt, as compared with the isomorphous mixture, a contraction has taken place and the specific gravity is too great.

Thus dolomite has the specific gravity 2·872 instead of 2·843, which ought to be that of a mixture of calcite and magnesite in equal molecular proportions.

Hence when the solutions of two isomorphous salts are mixed the result may be either (1) crystallised mixtures whose specific gravities are a *continuous function* of their composition, changing uniformly with the latter as though they were mechanical mixtures, or (2) a double salt whose specific gravity cannot be deduced from those of the constituents as though it were a mechanical mixture. In the double salt the proportions of the constituents are molecular, in the solid solutions they are not necessarily so.

Now what has been established for the specific gravity is equally true for the other physical properties (both general and crystallophysical) of solid solutions: the melting point, for example, and the refractive indices.

In mineralogy the specific gravity and the optical properties are those in which the relations can be most easily traced, and they are of the greatest practical importance.

8. **The Optical Properties of Solid Solutions.**—When two isomorphous cubic substances, two alums for example, crystallise together, the refractive index of the mixed crystals is found to vary continuously with the composition. Fig. 378 summarises the observations made on mixtures of potash-alum and thallium-alum.

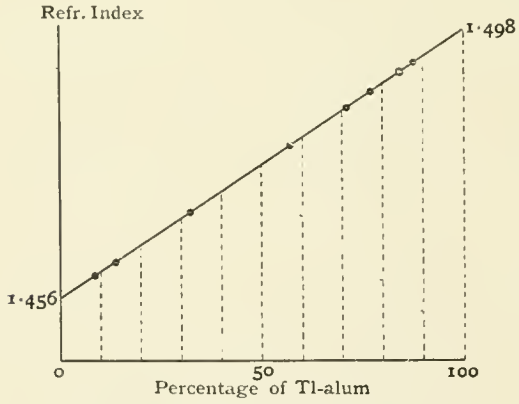

Fig. 378.—Mixture of Potassium-Alum and Thallium-Alum.

The eight points represent eight mixtures; the distance of each from the vertical axis represents the proportion of thallium-alum which it contains; its distance above the horizontal axis represents the refractive index. Just as was the case with the specific gravity, the points are found to lie on a continuous line.

Similarly with uniaxial mixtures, either of the refractive indices ω or ϵ, treated in the same way, will give a continuous line; in biaxial mixtures of orthorhombic crystals three continuous lines can be constructed to represent the variations of the three principal indices $\alpha\ \beta\ \gamma$, which in this system belong to fixed directions.

Each refractive index of the mixtures is therefore a continuous function of the composition.

It may, of course, happen that of two isomorphous uniaxial substances, one is positive and the other is negative. Thus in the case of the two substances whose optical characters are denoted by Fig. 379 (representing the axes of the indicatrix) the solution of increasing proportions of II in I tends to increase the index ϵ in comparison with ω; for one definite mixture, therefore, the two indices will become equal for a certain colour and the crystals will be isotropic for that colour. Thus the salt $SrS_2O_6 . 4H_2O$ is negative with weak double refraction; while the iso-

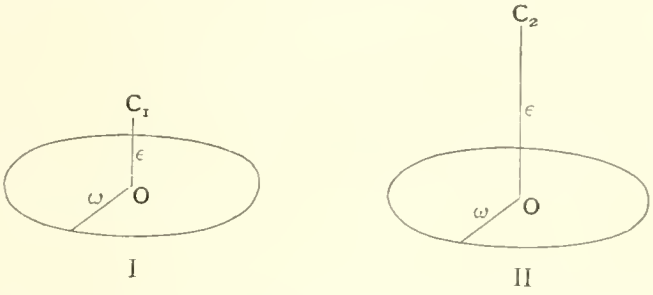

Fig. 379.—Mixture of Negative and Positive Uniaxial Substances.

morphous salt $PbS_2O_6 . 4H_2O$ is positive with stronger double refraction; both salts are hexagonal and possess the symmetry of quartz. A mixture which contains 17·9 per cent of the lead salt is absolutely isotropic for sodium light.

Consider, in the same way, two orthorhombic crystals (Fig. 380), in which the corresponding crystal axes are parallel, the vertical axis in each is the acute bisectrix, and AC in each is the plane of the optic axes; but I is positive (Ac . Bis = γ_1), and II is negative (Ac . Bis = α_2); for a

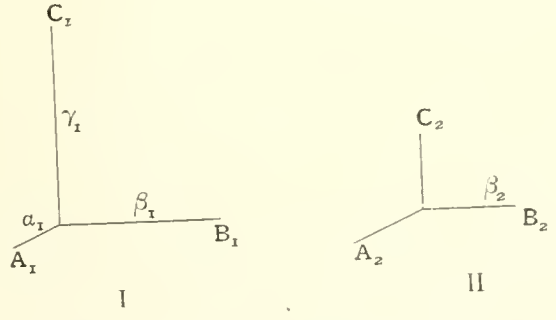

Fig. 380.—Mixture of Positive and Negative Biaxial Substances.

certain mixture α may have a value between α_1 and γ_2, equal to β, and the crystal may become uniaxial for some colour.

From these two examples it is clear that an isomorphous mixture of two substances may exhibit a physical symmetry apparently higher than that which belongs to either of them.

In the monoclinic and anorthic systems the relations are far more difficult to follow, for not only do the magnitudes and ratios of the refractive indices vary, but also the orientation of the indicatrix within the crystal. Nevertheless the same principle holds good, and the orientation of the

indicatrix, like all the physical properties, changes gradually with the proportions of the constituents.

The really important feature of solid solutions is that they are homogeneous crystals and therefore possess a definite indicatrix, whereas a mere mechanical mixture of crystalline particles of one substance with crystalline particles of another transmits light between crossed nicols without definite extinctions or interference figures, and is said to exhibit "aggregate polarisation."

In most crystals the positions of the optic axes are far more easy to determine than the refractive indices, and since these positions are functions of the latter they are also themselves continuous functions of the composition, like the specific gravity or any other physical character. Thus in mixtures of K_2SO_4 with $(NH_4)_2SO_4$—both orthorhombic salts—the following results have been obtained :—

In K_2SO_4 the optic axes are in the plane (100) and the axial angle in oil (2H) is 116° 26′.

As the proportion of the ammonium salt in the crystals increases, the axial angle diminishes, until with 19 per cent the crystals become uniaxial ; as the proportion is still further increased the optic axes open out again, but in the plane (001), which remains the plane of the optic axes until the pure ammonium sulphate is reached.

In $(NH_4)_2SO_4$ the optic axes are in the plane (001) and the axial angle in oil (2H) is 83° 30′.

The change closely resembles that which may be produced by change of temperature in a single crystal.

In the case of monoclinic and anorthic minerals the optic axial angle and the extinction angles of certain faces are practically the only characters available, since the orientation of the indicatrix and the measurement of the principal indices in these systems is a matter of great difficulty.

9. **Optical Properties of the Felspar Group.**—Among transparent minerals no group has been so thoroughly studied as that of the felspars.

These minerals are the most important constituents of the igneous rocks, whose nature, in fact, depends very largely upon that of the felspar which they contain. The crystals are generally very small and without faces, since they are embedded among other minerals. To identify the particular felspar of any igneous rock is always a problem of the utmost importance to the geologist.

The specific gravity can be determined by heavy solutions, by which, also, the felspar can be separated for analysis from the other minerals of the rock when it has been crushed to a powder. But for ordinary identification the rock is cut into thin transparent sections and the various minerals are identified by their optical properties under the microscope. And so it happens that, as regards composition, specific gravity and all the optical properties, the felspars have been exhaustively studied ; they are up to the present the only group of minerals in which the continuous variation of physical properties has been successfully traced throughout the group and has been proved to be such as is completely characteristic

of a solid solution. We can, therefore, take them as a perfect example of the relations between the various properties of the minerals belonging to a group whose members are not only isomorphous, but mingle as solid solutions.

It has been established by Tschermak and others that those felspars which contain both soda and lime can always be regarded as isomorphous mixtures of the soda-felspar, albite, $NaAlSi_3O_8$, with the lime-felspar, anorthite, $CaAl_2Si_2O_8$.

In spite of their apparent difference of composition these substances certainly form solid solutions in the most various proportions. Both albite and anorthite belong to the anorthic system and may crystallise in the form of Fig. 381.

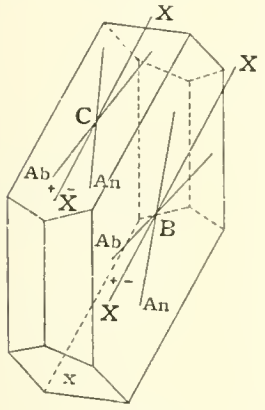

Fig. 381.

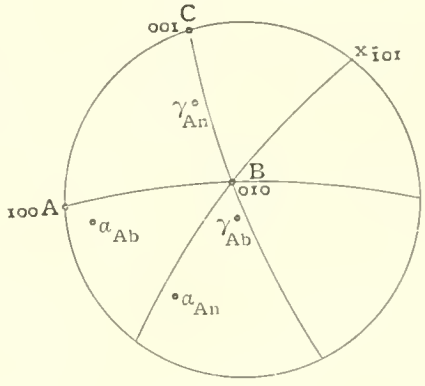

Fig. 382.

Figs. 381, 382.—Optical Properties of Plagioclase Felspars.

Both possess perfect cleavages parallel to the faces B (010) and C (001).

For albite the cleavage angle BC = 86° 24′.
„ anorthite „ „ 85° 50′.

The directions of the indicatrix-axes are shown on the spherical projection of Fig. 382.

γ_{Ab} is the acute positive bisectrix of albite.
α_{An} is the acute negative bisectrix of anorthite.
α_{Ab} is the obtuse negative bisectrix of albite.
γ_{An} is the obtuse positive bisectrix of anorthite.

The true axial angle 2V is about 77° for each mineral; consequently when cleavage flakes are examined in convergent light:—

The face B for anorthite shows one optic axis on the edge of the field of view (Fig. 612).

The face B for albite shows both optic axes on the edge of the field of view (Fig. 610).

The face C for anorthite shows one optic axis on the edge of the field of view (Fig. 614).

The face C for albite shows no interference figure.

The extinction directions on C and B measured with reference to

their edge X are shown in Fig. 381 ; the inclinations for albite are in one direction, which is by convention called positive, those for anorthite are in the other or negative direction.

Now between albite and anorthite a whole series of intermediate felspars has been examined ; the gradual and regular variation of their properties is shown in the following table, in which the composition of certain members of the group is expressed as a mixture of a certain number of molecules of albite (Ab) with a certain number of anorthite (An).

Composition.		Spec. Grav.	Extinction Angle on B	Extinction Angle on C	Mean Refractive Index β.
Albite	Ab	2·624	+ 19°	+ 4° 30′	1·534
Oligoclase	Ab_3An_1	2·659	+ 4° 36′	+ 1° 4′	1·542
Andesine	Ab_1An_1	2·694	− 16°	− 5° 10′	1·558
Labradorite	Ab_1An_3	2·728	− 29° 28′	− 17° 40′	1·570
Anorthite	An	2·758	− 36°	− 37°	1·582

Since γ is the acute bisectrix for albite and a that for anorthite, one or more of the intermediate mixtures must have a true axial angle of 90°, for which the acute and obtuse bisectrices cannot be distinguished. This seems to be the case for Ab_1An_3.

Similarly, for one mixture the extinction angle on B, and for another that on C, must be 0°. The mineral Ab_3An_1 appears to have nearly straight extinction both on B and on C.

If the specific gravity, the extinction angles and the refractive indices for the mixtures were plotted out as in the preceding section, three continuous curves would be obtained, from which the characters of any desired mixture might be predicted. Similarly in Fig. 378, γ_{Ab} would gradually migrate to γ_{An}, and a_{Ab} to a_{An}, as the composition gradually changes from Ab to An.

It will be noticed that in the felspar group we have to regard NaSi as vicarious with CaAl. Albite and anorthite, although they form solid solutions with each other, can scarcely be called isomorphous in the original sense of that word ; the plagioclases are solid solutions, not necessarily isomorphous mixtures in the narrower sense.

Some authors restrict the term isomorphous not only to such substances as form mixed crystals, but among them to those in which the physical properties of the mixed crystals are continuous functions of the composition, so that they may be represented by a continuous curve, as with the specific gravity and refractive index in the cases quoted above.

In mineralogy we may content ourselves with the fact that such solid solutions exist without venturing to assert that all the members of a mineral group (*i.e.* what is often called an isomorphous group) can form solid solutions, or that solid solutions can only be formed by substances of quite similar composition. In the best established case, that of the felspars, albite and anorthite are not strictly analogous in composition ; and this may also be so with many other minerals.

10. **Intergrowths and Overgrowths of Different Minerals.**—From

the case of the felspars, then, it is clear that solid solutions exist among minerals; it is more than probable that all the difficulties encountered in the attempts to explain the intricate composition of many minerals, and the variations both in composition and physical characters of most minerals, are to be accounted for by the supposition that they are usually solid solutions.

It has been pointed out by Retgers that when one of the two constituents of a solid solution is colourless and the other coloured, the complete mixture of the two is indicated by the uniform coloration of the crystals. Thus Retgers found that potassium permanganate $KMnO_4$ mixes in uniformly coloured crystals with the colourless $KClO_4$, and KIO_4; and therefore that it is capable of forming a solid solution with a per-chlorate and with a per-iodate.

Now nothing is more common among minerals than to find perfectly clear homogeneous crystals of the most widely different colours, although they belong to the same mineral. Garnet is not only colourless but also, and more often, black, brown, or yellow, sometimes also red or green. The smallest proportion of a coloured constituent may alter the whole aspect of the substance.

The almost universal occurrence of mixed crystals in the mineral kingdom makes it probable that the equally common variations of colour are often to be ascribed to the intermingling of variously coloured isomorphous compounds.

If the constitution of the mixture changes during the growth of such crystals the colour of the crystals will also change, and consequently the same crystal may be differently coloured at its two ends, or may show successive bands of differently coloured material; this is also frequently observed in minerals; in tourmaline, for example, a prism of one colour often seems to be enclosed within a prism of another colour. Such a crystal is not an intergrowth but an overgrowth of two substances.

If a crystal of chrome-alum be immersed in a saturated solution of potash-alum, a slight re-solution of the crystal will take place, but will be immediately succeeded by a crystallisation of the latter salt, which proceeds to grow in parallel position upon the former; ultimately the crystal of colourless potash-alum will contain as a coloured kernel the crystal of chrome-alum: there has been a parallel overgrowth of the one of two isomorphous substances upon the other.

Similarly, in the case of the felspars, a crystal having one extinction angle may be enveloped by felspars having different extinction angles, constituting a "zoned" crystal in which the zoned structure is only visible between crossed nicols and reveals itself in a section by the extinction shadow that passes across the crystal, zone by zone, as the microscope stage is rotated.

Or the overgrowth may be of such a sort that isolated crystals of a substance A are deposited upon a crystal of an isomorphous substance B. so as to be all parallel to the latter. Thus crystals of one felspar sometimes lie in parallel position upon a crystal of another felspar (Fig. 383).

Like the mixtures or the intergrowth of two substances to form a

single crystal, so also the parallel growth of crystals of one sort upon another generally takes place between those which are analogous in chemical composition; but it may also take place between those in which the chemical relationship is very slight.

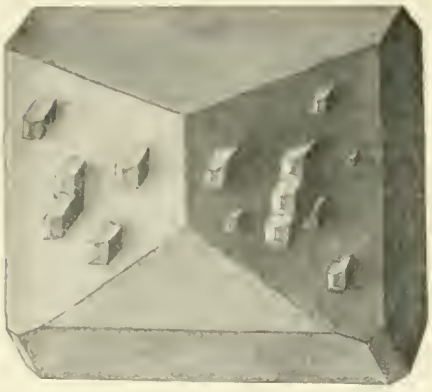

Fig. 383.—Albite in Parallel Position upon Orthoclase.

Thus sodium nitrate, $NaNO_3$, is almost identical with calcite, $CaCO_3$, in angles, in cleavage, in its mode of twinning and its optical properties, possessing also a very strong double refraction. The two substances are not soluble to the same extent in any known solvent, neither have they the same fusibility, and they do not form solid solutions.[1] But if a drop of sodium nitrate solution be placed on a fresh cleavage face of calcite, the little rhombohedra of the nitrate will be seen to deposit themselves in almost perfect parallelism upon the calcite, as in Fig. 384.

That this is not a mere chance relation is proved by the fact that KNO_3, which is isodimorphous with $NaNO_3$, crystallises in the orthorhombic system, with angles and twinning almost identical with those of aragonite, and is itself capable of crystallising in parallel position upon aragonite. Hence if the word isomorphism is to be allowed to include such cases, the nitrates $R'NO_3$ must be called isodimorphous with the carbonates $R''CO_3$.

Their mutual relationship appears to consist in the fact that the two molecules contain *the same number of atoms*, rather than in any close chemical similarity.

Another case of overgrowth is the parallel grouping of two (more or less) unlike minerals which happen to possess nearly the same form, as that of staurolite and cyanite (p. 86); and possibly also regular but not parallel growths of some minerals which appear to be quite unlike both in form and composition, as that of rutile with hæmatite (p. 86).

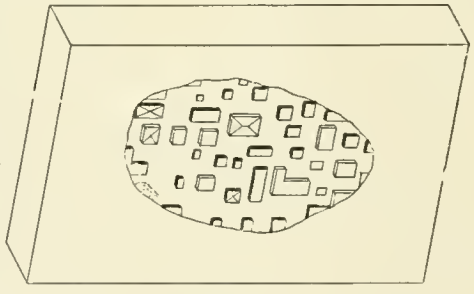

Fig. 384.—Sodium Nitrate crystallising on Calcite.

11. **Intergrowths and Overgrowths of the same Mineral.**—In all the mixed or associated growths considered above, the features are much the same; two compounds possessing not only nearly the same form but nearly the same internal structure (as is proved by their similarity of cleavage) can crystallise together,

[1] It must be remembered that mixed crystals and solid solutions are not exclusively the result of crystallisation from a common solvent, as with the alums, etc., but may result from the cooling of a fused mixture, as in the crystallisation of a slag, a volcanic rock, or an alloy, or even from the sublimation of mixed vapours.

either one upon another, or with such complete interpenetration that they unite to make a homogeneous crystal. In the completely homogeneous mixture or solid solution, the properties are such as might be expected to result from an intimate mechanical mixture of the one substance with the other; they can be predicted by adding the effect of one to the effect of the other in proportion to the amount of each; this is indicated by the gradual change of a general property, *e.g.* the specific gravity, as the composition gradually changes. Further, the particles cannot be regarded as mixed in confusion as they would be in a mere mechanical mixture, but in such a way that those of the one substance are as nearly as possible parallel to those of the other; this is indicated by the gradual change of a crystallophysical property, such as an extinction angle or a particular refractive index. When, for example, the index β of the intermediate felspars is found to be a continuous function of the composition, it is clear that in the mixture of albite with anorthite the mean axis of the indicatrix of each mineral maintains its direction in all the mixtures. The same conclusion may be drawn from the fact that the cleavage generally remains unchanged in a series of isomorphous mixtures. In other words, the solid solution is a mechanical mixture in which the particles are arranged in an orderly manner, and parallel to each other, like those of a simple crystal.

Now all these features suggest very forcibly an analogy with twinning, especially the hemitropic types; there, also, two crystals are associated either one upon another or by interpenetration. In twins, however, the two crystals are not parallel, so that they cannot constitute a homogeneous crystal, neither can they possess, in general, the optical characters of a single crystal.

If it be supposed that a crystal consists of particles arranged in a uniform and orderly manner, twinning may well be due to the fact that after one individual has been turned into the twin position the orderly arrangement of its particles is nearly the same as before; in a juxtaposition twin the arrangement may only be the same in the composition plane, where the two individuals come into contact; in an interpenetration twin the arrangement may be the same throughout.

This explanation seems very reasonable, and the resemblance between twins and isomorphous mixtures is very close in the case of pseudo-symmetric crystals. In a mimetic mineral like aragonite it is clear that the crystal possesses nearly trigonal symmetry about its vertical axis so far as its external form is concerned, and probably, therefore, in its internal structure also. Hence a rotation of about 120° round the vertical axis (Fig. 368) will bring the structure *nearly* into coincidence with itself, and the two individuals will be free to intermingle. In a pseudo-symmetric crystal the resemblance is even closer; the structure of boracite is so nearly that of a cubic crystal that it is nearly coincident with itself after an appropriate rotation about any of the axes of pseudo-symmetry. Hence during crystallisation the particles are free to deposit themselves either in parallel or in twin position, and the result is so nearly a uniform cubic crystal that the mineral can only be distinguished from a cubic one

by its optical properties. In such a structure the slightest change in the relative position of the particles, a slight separation in one direction or a slight contraction in another, may make the structure absolutely cubic; this change appears, in fact, to occur when the crystal of boracite is heated to 265° and becomes isotropic.

12. **The Structure of Minerals.**—All the peculiarities which more or less distinguish the physical and chemical properties of minerals, as compared with other substances, can now receive a systematic description as due to the *intergrowth and overgrowth of nearly identical structures.*

Crystals clearly grow by the accretion of particles of some sort; that the arrangement of the particles is uniform and regular, and that they are parallel to each other is probable from the homogeneity of crystals. Twinning and pseudo-symmetry are, on this assumption, due to the fact that the same particles may fit almost equally well into the structure in the twin position or positions as in the parallel position.

Similarly if two different compounds crystallise in structures which are nearly identical they may mix to form (1) regular overgrowths, (2) more or less complete mixtures, or, (3) when the structures are sufficiently similar, true solid solutions. In the last case there is generally a very close relationship between the two substances as regards chemical composition.

The intergrowth may, further, take place not only in parallel but in twin position, so that, in the former case, the isomorphous mixture may give rise to a homogeneous crystal (solid solution), in the latter to a pseudo-symmetric crystal showing the so-called optical anomalies. The intermixture may in any case be of more than two kinds of particles; those felspars, for example, which contain potassium as well as sodium and calcium, are mixtures of albite, anorthite, and a potassium felspar.

Again, the particles of a given compound may be arranged in different ways and give rise to more than one structure (polymorphism), but intergrowths of the nature which we are considering will only take place between the similar structures. This was seen to be the case with the isodimorphous mixtures of § 6.

It has been urged that one structure can only fit into the other if the particles (not necessarily in contact nor of the same size) occupy nearly the same space. Now the specific gravity of a mineral is proportional to the weight of its particles and inversely proportional to the space which they occupy, and, if the arrangement be the same in a series of isomorphous substances, the weight of the particles may perhaps be proportional to the molecular weight of the substance; hence it has been suggested that the space which they occupy may be represented by the molecular volume, *i.e.* by the ratio

$$\frac{\text{molecular weight}}{\text{specific gravity}}.$$

This quantity, the molecular volume, might therefore be expected to be constant, or nearly constant, in an isomorphous series, although the specific gravity may vary largely according to the composition. Thus

the specific gravity of strontianite, $SrCO_3$, is 3·7, that of cerussite, $PbCO_3$, is 6·5; but they have the same molecular volume, 41. So also albite and anorthite possess the same molecular volume, 101. Hence, according to some authors, the capacity of these minerals to mingle as a solid solution.

In some isomorphous series there is not equality of the molecular volume throughout, but they seem to differ by equal quantities, so as to form an arithmetic series.

For a better knowledge concerning the particles of which a crystallised mineral consists, far more information about its chemical constitution is required. In solid solutions, as we have seen, the physical properties are a direct additive result of the chemical composition; but when two constituents unite in molecular proportions to form a double salt, this is not the case; it is as though the particles were no longer arranged beside each other but were united by a closer bond. In this case there is generally some contraction in bulk; thus (as stated above) the specific gravity of dolomite, $CaCO_3 . MgCO_3$, is 2·872, whereas that of an isomorphous mixture of calcite and magnesite in these proportions would be 2·843. It is, nevertheless, possible that dolomite may be isomorphous with calcite and magnesite, though not a solid solution of these two compounds, and though its symmetry is not quite the same.

In other cases the form and symmetry of the double salt differ entirely from that of the constituents.

Thus aragonite and witherite form isomorphous mixtures, $(Ca,Ba)CO_3$, having their own orthorhombic form; but they also make a double salt, $CaCO_3 . BaCO_3$, belonging to the monoclinic system.

Little is yet known of the change in properties produced when two or more constituents unite to make a double salt; equally little is known about the morphotropic action of different elements or radicles in minerals; still less is known about the nature of the particles of which minerals consist, how many chemical molecules they contain, or even how the molecules and their atoms are united.

Still, enough has been said in the preceding sections to show how it is that one and the same mineral may vary quite widely in its properties and in its composition, since it may not only be a pseudo-symmetric twin of the same or of different materials, and so may possess apparently anomalous physical characters, but it may further be a solid solution, or, at any rate, a mixture of several definite constituents, and may apparently defy the law of simple atomic proportions. All these apparent anomalies and inconsistencies are to be regarded as the result of the crystalline structure, and due to the fact that two or more nearly identical structures may unite to form a single crystal.

Although in the case of most minerals the constituents are not known and cannot be isolated, yet the variations which they produce must be of an orderly and regular character; it is mainly by a study of these variations (as has been done for the felspars) that the nature of the constituents and their properties will be traced. The study of the properties of minerals will then be the study of the nature and the arrangement of the particles which constitute the solid crust of the earth.

BOOK IV

THE DESCRIPTION AND DETERMINATION OF MINERALS

CHAPTER I

DESCRIPTIVE TERMS

It has been shown above how, owing to isomorphous and other intermixtures, a mineral species must possess very variable characters, but that these characters vary together in a regular and uniform manner.

We have now to see how different specimens of one and the same mineral may present many irregular varieties of aspect, even when they are identical in their form and crystallophysical properties, in their specific gravity and chemical composition.

These varieties of aspect are chiefly due to the different ways in which minerals may be aggregated, and to the great variety of colour which they present, not only as solid solutions but also owing to the enclosure of impurities.

Before the study of the essential properties was developed the external aspect, and what may now be called the "inessential" characters, were mainly relied upon by the "natural-history" school for the discrimination of species (see p. 195). Minerals were mainly distinguished not only by their crystalline form, but also by such characters as colour, lustre, hardness, fusibility, and the form and structure of their aggregates; consequently a great number of species- and variety-names were given, on account of differences in these inessential characters, and were given to minerals which we should now refer to the same species.

These characters and the names relating to them are still largely used by mineralogists; among them the hardness, the streak, and the lustre are of considerable value in the practical determination of minerals: the remainder are chiefly useful in the description of specimens.

1. **Morphological and Structural Characters—Habit.**—Although every mineral which crystallises has only one characteristic crystalline form, yet any crystal may assume various shapes, due to a more rapid growth in one direction than another. A cube of sodium chlorate, for example, crystallising on the bottom of a beaker can grow more rapidly in a lateral than a vertical direction, and therefore becomes a tablet, whereas if suspended within the solution it would grow evenly and remain a cube. The shape which the crystal presents to the eye is called its "habit," and the habit is due, not to the nature of the substance, but to the conditions which have prevailed during its growth. It is there-

fore not a constant, but a variable character. A crystal of albite may have either of the two forms of Fig. 385, but the *angles* between corresponding faces are the same in both.

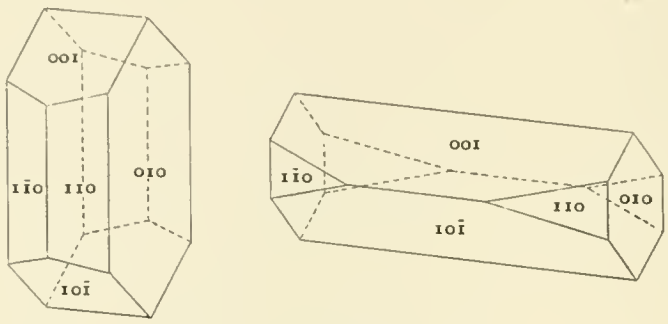

Fig. 385.—Two Habits of Albite.

The following varieties of habit are distinguished by mineralogists:—

Tabular.—When one pair of parallel faces is much larger than the others, as in Fig. 387, the mineral is said to crystallise in "tables" or "plates," *e.g.* the hæmatite ("iron glance") from Cumberland.

Prismatic.—When the crystal is elongated in one direction the mineral is said to crystallise in "prisms," *e.g.* tourmaline, which almost always has a prismatic habit. When a prismatic crystal is bounded at one end by crystal faces it is said to be "terminated"; if at both ends it is said to be "doubly terminated." Many minerals, such as quartz, generally spring from the sides of a vein or cavity to which they are attached by

Fig. 386.—Acicular Cerussite.

one end; hence doubly terminated crystals of such minerals are comparatively rare.

Pyramidal.—When the predominant faces meet in an apex or in a pair of opposite apices the mineral is said to crystallise in "pyramids"

or bipyramids. Anatase almost always has a pyramidal habit. Different pyramids are distinguished by the form of their base. Anatase shows a bipyramid with square base (Fig. 118); sulphur, with rhombic base (Fig. 142); quartz, with hexagonal base (Fig. 156). Witherite is pseudo-hexagonal, and also has an apparently hexagonal base.

Acicular.—When the crystals are long and very thin the mineral is said to be "acicular," or to crystallise in "needles," *e.g.* scolecite from Bombay, or cerussite from Cornwall (Fig. 386).

Capillary.—When the crystals are so thin as to be like fine threads or hairs they are said to be "capillary," *e.g.* millerite from Merthyr-Tydvil.

The above characters depend only on the relative dimensions of the faces. They are not essential, because the same mineral may occur in one place in crystals of one habit, at another place in crystals of quite a different habit. Thus barytes generally occurs in tabular crystals (Fig. 387), but that from Betler in Hungary is found in prisms which have

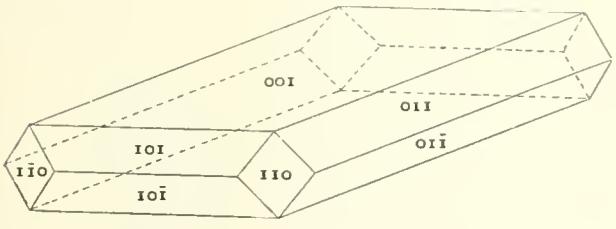

Fig. 387.—Tabular Barytes.

Fig. 388.—Barytes from Hungary.

such a different aspect (Fig. 388) that they were originally described as a new mineral under the name "wolnyn."

Cuprite often crystallises in very perfect cubes, but it is also found in capillary crystals (elongated cubes), which were once regarded as a distinct variety, and received the name of chalcotrichite.

Surface Characters of Crystal Faces.—These are distinguished as *smooth*, *rough*, and *curved*. When smooth they possess an evenness and brilliancy which can scarcely be imitated by any artificial polish, and reflect perfectly clear images of distant objects. This property is utilised in the measurement of crystals by the reflecting goniometer (p. 100). In a perfect crystal the faces are both plane and smooth.

Among the varieties of rough faces two are distinguished by special names.

Drusy faces are those which are composed of minute projecting crystals, as described on p. 84, *e.g.* the tetrahedrite from Herodsfoot mine, Liskeard, Cornwall, where the druisiness is due to a coating of chalcopyrite (cf. Fig. 393).

Striated faces are marked in one or more directions with fine parallel

lines or furrows resembling scratches. These lines are called "striæ"; they may be due (1) to repeated twinning, as in albite (Fig. 244, p. 93);

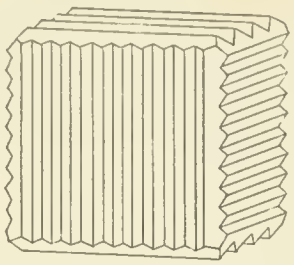

Fig. 389.—Oscillatory Combination.

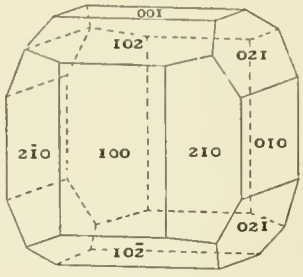

Fig. 390.—Pyrites.

(2) to a repetition of minute crystal faces, as in pyrites (Fig. 82, p. 43). In Fig. 389 the crystal is an "oscillatory" repetition of {210} simulating the combination of Fig. 390.

The *curvature* of faces is generally due not to an oscillatory, but to a

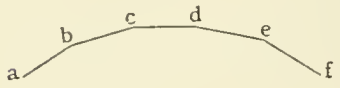

Fig. 391.—Succession of Faces producing Curved Face.

Fig. 392.—Lenticular Gypsum.

progressive succession of vicinal faces (Fig. 391); thus if the angles between the successive vicinal faces *ab*, *bc*, *cd*, *de*, *ef* be sufficiently small, *af* will approximate to a curved surface; when this is so pronounced as to give rise to a lens-shaped crystal, the latter is called *lenticular*. Many crystals of gypsum from Montmartre, near Paris, are lenticular.

Fig. 393.—Drusy Crystal of Fluor.

Aggregation of Crystals. — When two or more crystals are united their union may be either regular—in which case it is due to their crystalline structure—or irregular.

The regular conjunction (which was described in Chap. II. p. 84) is of two kinds, parallel growth and twinning. The druseiness of crystal faces is generally due to a coating of minute parallel crystals; striations and re-entrant angles are often produced by twinning. Fig. 393 represents

a drusy crystal of fluor, a polysynthetic octahedron composed of cubes.

Irregular conjunctions are distinguished as—

Radiating, when the crystals diverge from a centre. This is generally characteristic of prismatic and acicular crystals, *e.g.* wavellite (Fig. 394).

Rosette-shaped, when they overlap round a centre like the petals of a rose. This is characteristic of tabular crystals, *e.g.* hæmatite from St. Gothard (Fig. 395).

Fig. 394.—Radiating.

Fig. 395.—Rosette-shaped.

Reticulated, when sets of parallel crystals interlace and are matted together; the reticulation of the rutile from Tavetsch in Switzerland, known by the name "sagenite," from σαγήνη, a net, is due to twinning (Fig. 396).

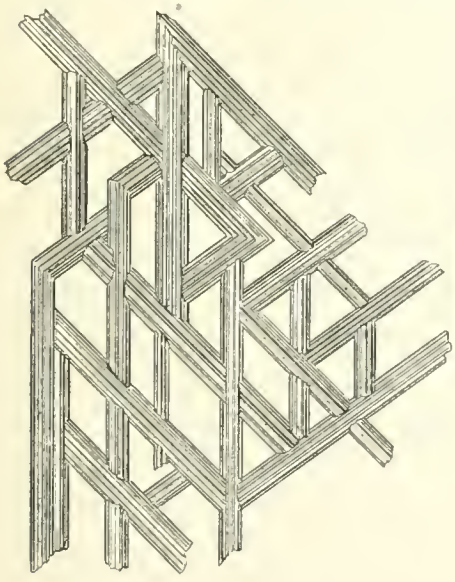

Fig. 396.—Reticulated.

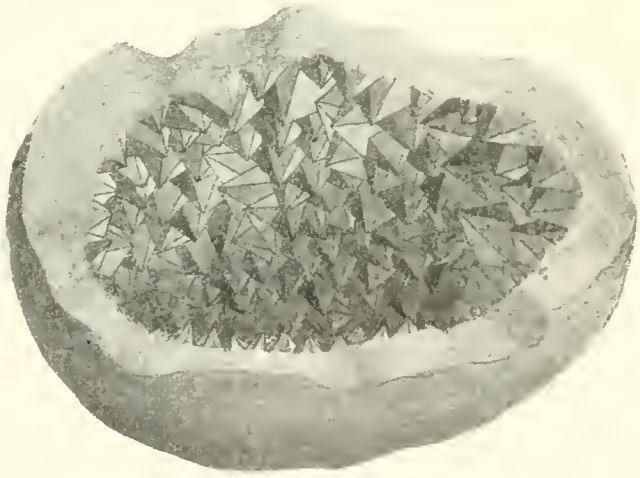

Fig. 397.—Quartz Geode.

Geodes.—Crystals lining a cavity constitute a geode. Such cavities are also called "druses." The "potato-stones" from Bristol are hollow brown nodules of quartz lined with crystals of the same mineral (Fig. 397); the cavities in flints are often lined in the same way.

Form and Structure of Crystal Aggregates.—Both the external

form assumed by crystalline aggregates, and their internal structure, depend upon the shapes and the mode of aggregation of the constituent crystals. Some of these forms and structures are very characteristic of certain minerals, and they are of importance as indicating in some instances the mode in which the minerals have been formed.

Form.—The following names are used to describe the common forms of mineral concretions.

Dendritic (branched or arborescent), when the constituent crystals diverge from each other and from a common stem, so as to resemble a frond. This is essentially due to a crystalline structure (often to twinning), and is illustrated by the manner in which ice crystals form "frost figures" on glass. Among minerals common examples are native copper (Fig. 398)

Fig. 398. Dendritic Copper.

or the frond-like growths of pyrolusite sometimes found in sandstone (Fig. 399).

Mossy.—A similar form in which the sprays and leaflets are more minute. This is also essentially crystalline. Mossy inclusions of chlorite give its name to moss-agate (Fig. 400).

Leafy.—Some minerals, especially the native metals, occur in thin plates or leaves, *e.g.* gold.

Filiform (or wiry).—Silver is occasionally found as fine wires.

Globular.—Many minerals occur in spherical concretions, which are generally due either to the deposition of successive coats round a central granule, like the coats of an onion, as in the pisolites of calcite or aragonite (Fig. 401), or to a radial structure in which the constituent crystals radiate from a centre, as in wavellite (Fig. 394).

Nodular, when the mineral occurs in irregular lumps or nuggets.

Warty, resembling growths of warts.

Mamillary, resembling the nipples of the breast.

Reniform or kidney-shaped.—The opal, "menilite," of Menilmontant, near Paris, is a typical example.

Coralloidal, resembling coral in form, *e.g.* the aragonite or "flos-ferri" of Eisenerz in Styria (Fig. 402).

Botryoidal, resembling a bunch of grapes. Fig. 403 represents a botryoidal group of dolomite; but the name is often made to include all

Fig. 399.—Dendritic Pyrolusite.

such rounded forms as those of Fig. 404, which represents a specimen of hæmatite from Cumberland.

Amygdaloidal, or almond-shaped.—The kernels filling steam vesicles or pores in volcanic rocks are known as *amygdules*; they are often hollow and lined with crystals; Fig. 405 represents a broken amygdule.

Stalactitic, resembling stalactites, or icicles, and, like the former, often formed by dripping solutions; generally cylindrical and composed of crystals radiating perpendicularly from the central line or axis (Fig. 406).

Structure.—To describe the varieties of internal structure which

Fig. 400.—Moss-agate.

accompany the above forms of crystalline aggregates the following terms are used :—

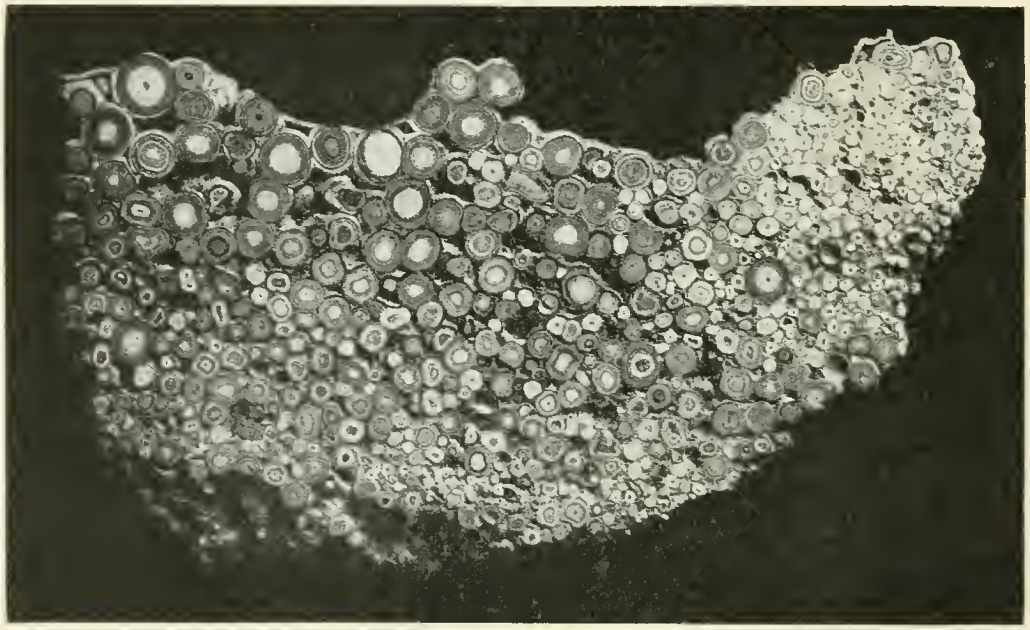

Fig. 401.—Pisolite (section).

Laminar (or lamellar), when the constituent crystals or aggregates are tabular and parallel to each other. The terms *micaceous* and foliated are also used.

Columnar, when the constituent crystals or aggregates are prismatic and parallel to each other.

Fig. 402.—Flos-ferri.

Fibrous, when the constituent crystals or aggregates are acicular or capillary.

Fig. 403.—Botryoidal Dolomite.

Granular, when composed of grains or small irregular-shaped crystals.

Massive, when the outlines of the constituent crystals cannot be distinguished by the eye.

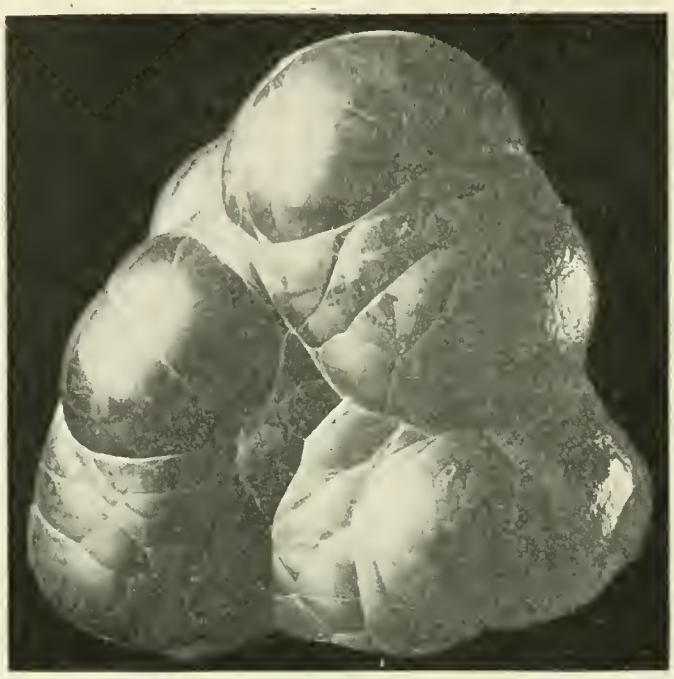

Fig. 404.—Botryoidal Hæmatite.

Compact, when the constituent crystals are completely invisible to the eye.

Curvilaminar, when composed of curved layers.

Powdery, when composed of minute crystals or grains which are not coherent.

Amorphous Minerals. — Amorphous minerals are of two kinds, *vitreous* (or glassy) and *earthy*.

When vitreous they are uniform masses without visible structure, and devoid of any crystalline form or structure. When earthy they are composed of coherent or loosely coherent particles, which are not crystalline.

Fig. 405.—Amygdule.

Amorphous minerals may assume the various forms described above as globular, nodular, warty, mamillary, reniform, coralloidal, botryoidal, amygdaloidal. Since, however, they are devoid of crystalline form, the definition of a species which is only known to occur in the amorphous condition can never be regarded as complete. An example of a truly amorphous mineral is opal (colloid silica), which has never been found in crystals.

2. **Characters depending upon Cohesion — Elasticity, etc.** — A mineral in which the constituent particles are coherent opposes a resistance to any force which tends to alter the *relative* positions of the particles.

If the cohesion is sufficient to prevent any permanent deformation, the particles return to their original position when the force is withdrawn, and the mineral is said to be *elastic*. Such a substance may be to a certain extent bent without breaking, and will return to its original shape. A typical example among minerals is mica, of which the thin sheets and leaves obtained by cleavage are extremely elastic.

Elasticity as measured by the extension or compression experienced in a bar of known dimensions under the action of a known weight is, as we have seen, a character capable of exact measurement, and one of considerable theoretical importance, but it is of little value in the practical determination and description of crystalline aggregates and minerals in general.

When the cohesion is not sufficient to restore the original form, the substance remains bent, and is said to be *pliable*. Talc, which in thin leaves might sometimes be confused with mica, is an instance of a pliable as opposed to an elastic mineral. The pliability of *mineral aggregates* is sometimes due to the interlocking of their particles. The flexible sandstone of Delhi consists entirely of angular quartz grains, which dovetail into each other, so that there is a slight play between the particles. In consequence of this structure plates and slabs of the Delhi sandstone may be bent in an extraordinary manner without breaking.

Fig. 406.—Stalactite.

When the particles of a mineral are capable of moving over each other to a considerable extent without losing their cohesion, the mineral is said to be—

Sectile, when it can be cut with a knife without breaking.

Malleable, when it can be flattened by pressure or by a blow with a hammer.

Ductile, when it can be drawn into strips or wires.

Some of the native metals are malleable and ductile; they are, of course, also sectile; every ductile substance is also malleable.

The only common sectile minerals are the following:—

Elements—*Graphite*, *bismuth*, *copper*, *silver*, *gold*, *platinum*.

Sulphides—*Copper glance*, *stromeyerite*, *argentite*, *dyscrasite*, *molybdenite*, *orpiment*, *tetradymite*.

Oxides—*Senarmontite*, *arsenolite*.

Haloids—*Cerargyrite*.

When the particles are free to move over each other to any extent, the mineral is *liquid*, like water or mercury.

Frangibility.—When the force applied is sufficiently great, the cohesion is overcome, the particles are finally torn asunder, and the mineral is fractured.

The frangibility of any material is measured by determining the

breaking strain, or the weight required to fracture a bar of given dimensions. In mineralogy it is only of importance as a determinative quality which is estimated, not measured.

Thus the **tenacity** or degree of frangibility is distinguished by the following terms:—

Brittle, *tough*, *soft*, *friable*.

The **fracture** or nature of the broken surface is distinguished as—

Conchoidal, when it is curved like a shell; *e.g.* quartz.

Sub-conchoidal, when it is slightly conchoidal; *e.g.* crystals of hæmatite.

Uneven; *e.g.* tourmaline.

Even; *e.g.* chalcedony.

Splintery, when it is like the broken surface of wood. This is especially characteristic of minerals with a fibrous structure; *e.g.* jade.

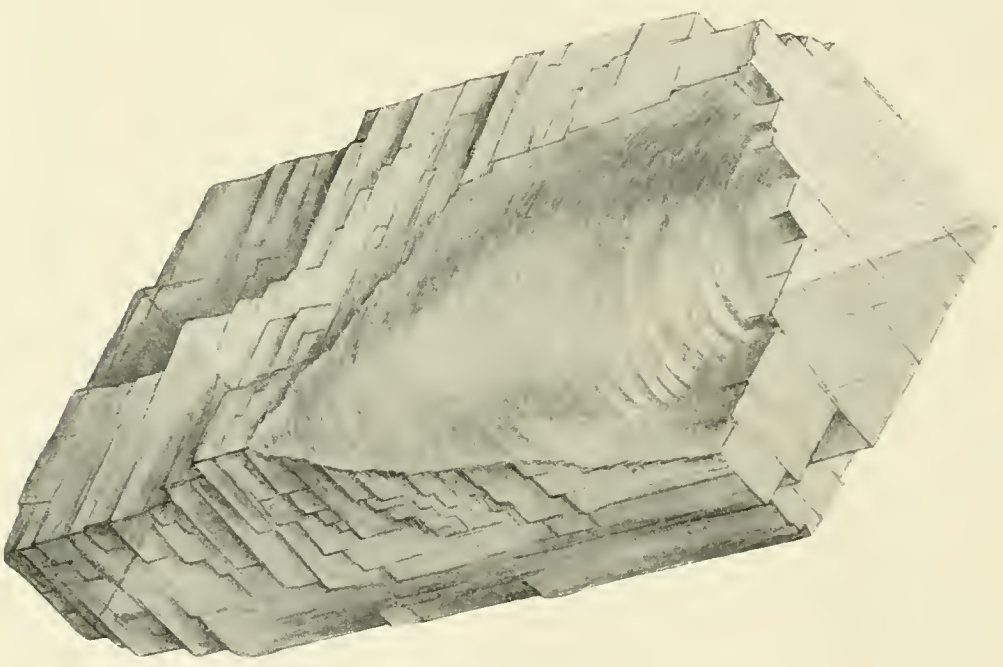

Fig. 407.—Calcite showing Conchoidal Fracture and Cleavage.

Hackly, when it is jagged and rough. This is especially characteristic of some metals, and is due to their granular-crystalline structure; *e.g.* copper.

Both crystals and crystalline aggregates display these varieties of fracture, but crystals also possess the property of plane cleavage, which has been described above. The fracture is difficult to obtain in crystals like calcite, which possess a very facile cleavage, since the crystals generally cleave and will not break in any other way.

Fig. 407 represents the rare conchoidal fracture of calcite.

Parting and Cleavage. — The *crystals* of some minerals separate along parallel plane surfaces which are not true cleavage planes, for the crystal cannot be cleaved at any part so as to yield very thin plates,

but only at certain intervals. This *parting*, as it is called, probably takes place along glide-planes or planes of secondary twinning (p. 95). Magnetite, for example, possesses an octahedral parting, but not cleavage.

Hardness.—When pieces of two substances are rubbed together, one is generally found to scratch the other without being itself scratched. It is then said to be the harder of the two. The hardness is best tested by drawing the sharp corner of one substance along a smooth surface of the other. The scratch which is made is a line along which the particles have been thrust asunder until their cohesion has been overcome. Thus the hardness depends upon the degree of cohesion. This character is one of considerable value in the determination of minerals.

For this purpose a comparative "scale of hardness" was devised by Mohs for the use of mineralogists, as follows:—

Mohs' Scale of Hardness

1. Talc.	6. Orthoclase.
2. Gypsum or rock salt.	7. Quartz.
3. Calcite.	8. Topaz.
4. Fluor.	9. Corundum.
5. Apatite.	10. Diamond.

The hardness of a mineral is estimated by its capability of scratching, or being scratched by, any mineral in the above list.

A mineral which can scratch fluor, but not apatite, is said to have a hardness between 4 and 5.

The hardness as estimated in this way is no more than a rough approximation, and is by no means a quantity which can be accurately measured; yet in experienced hands it becomes a very valuable aid in the determination of mineral species, since many minerals which resemble each other closely in appearance differ widely in their hardness. For instance, copper pyrites ($H = 3\frac{1}{2} - 4$) may be readily distinguished from iron pyrites ($H = 6 - 6\frac{1}{2}$), since the latter is only with difficulty scratched by the knife, while the former yields readily. Again, beryl and apatite are easily confused by their appearance, but beryl has a hardness of nearly 8, whereas that of apatite is only 5.

Where other means of determination are wanting, and even when no minerals belonging to the above scale are available for comparison, the degree of ease with which a mineral may be scratched by the knife is often of the greatest possible use.

Minerals whose hardness is not greater than 2 are scratched by the finger nail; those of greater hardness than 6 are not scratched by the knife. In many classes of minerals the compounds of silver, copper, mercury, and lead are relatively soft, those of iron, nickel, and cobalt are relatively hard. Minerals, such as corundum, which, although not compounds of the heavy metals, possess a high specific gravity, possess also

great hardness. The hardness of a mineral aggregate is generally less than that of the crystallised mineral itself.

The determinative value of hardness is diminished by the fact that, like all characters which relate to a direction, it is different for different directions upon the same crystal, being especially low along directions of cleavage; these variations are, however, slight, and are, generally speaking, far below the intervals between successive numbers on the scale of hardness. In cyanite, however, the hardness is 7 on the face (010) and only 4 in one direction on the face (100).

3. **Optical Characters.**—When light falls upon a mineral it is partly reflected from the surface and partly refracted into the mineral. A part of the refracted light is reflected inside the mineral, and emerges again to mingle with that reflected at the surface; a part is absorbed; and in transparent minerals a part is transmitted through the substance and emerges on the other side.

The superficial optical characters (lustre and colour) are due to the intensity and nature of the reflected light, and of that which penetrates only to a small depth in the crystal; certain other characters (transparency, fluorescence) are due to the intensity and nature of the transmitted light, or of that which penetrates further into the crystal. Both the reflected and refracted light become partly polarised.

Lustre.—The intensity and nature of the reflected light are included under the term "lustre"; and according to its degree of intensity the lustre is described as either *splendent*, *shining*, *glimmering*, or *dull*; it depends to a large extent upon the nature of the surface, the most brilliant being produced by very smooth surfaces and very opaque material. This is exhibited by some of the more opaque minerals, especially upon plane crystal faces or a smooth fracture.

The nature of the reflected light gives rise to a certain characteristic surface appearance, to which the term lustre more particularly applies; this is at least partly due to the structure of the mineral.

The lustre is distinguished as—

Metallic—like the surface of polished metal; peculiar to certain opaque minerals; *e.g.* galena.

Adamantine—nearly approaching metallic, but characteristic of minerals which are transparent, or partly so; *e.g.* cerussite.

Resinous—like the surface of broken resin; *e.g.* pyromorphite.

Vitreous—like the surface of broken glass; *e.g.* quartz.

Waxy—like the surface of wax; *e.g.* chalcedony.

Pearly—like mother-of-pearl; generally accompanied by a laminated structure; *e.g.* talc.

Silky—generally characteristic of a fibrous structure; *e.g.* gypsum.

Intermediate varieties are sometimes distinguished as sub-metallic, metallic-adamantine, metallic-pearly, etc.

True metallic lustre is nearly confined to metals and their com-

pounds with sulphur, arsenic, antimony, and bismuth; both this and adamantine lustre are characteristic of minerals with a very high refractive index, greater than 2. Thus the refractive index of diamond is 2·27; of blende, 2·37; of cuprite, 2·85; and these minerals all have an adamantine lustre. Many compounds of lead exhibit an inclination to resinous lustre.

Diaphaneity.—If objects can be clearly seen through a mineral it is said to be *transparent*; if light penetrates, but not sufficiently to enable objects to be seen, the mineral is said to be *translucent*: intermediate degrees of transparency are distinguished as semi-transparent and semi-translucent; the remainder are *opaque*, but many of these are feebly translucent in very thin sections.

Refractive Power.—Many of the superficial characters of minerals, whether crystals or aggregates, depend upon their refractive power. The accurate determination of the refractive index and its importance were considered in Chap. VII.

It will only be necessary here to mention the means by which it may be approximately estimated, and some of the characters which vary with it.

In looking at a transparent piece of pure glass it is easy to see the surface of the glass; this is because the surface is in contact with air. Immerse the glass in water which has more nearly the same refractive power, and its surface will stand out with less clearness of "relief"; immerse it in a liquid having exactly the refractive index of the glass, and it will become invisible.

Upon this principle is based a very convenient method of determining approximately the refractive index of a mineral: a small fragment is immersed in various liquids of known refractive index; that in which its surface is most nearly invisible has a refractive index nearest to its own.

Similarly there is a curious difference in the appearance of an immersed rough surface, according as the refractive index of the liquid is more or less like that of the mineral enclosed in it. If the mineral has an index equal to that of the liquid little or none of the light incident from above will be reflected, and the unevenness of the surface will not be visible; but if the mineral has an index different from that of the liquid, then some of the light incident upon the surface will be reflected, and the roughness will remain clearly visible. In this way it is easy to see whether the index of an ordinary mineral section mounted, as is usual, in Canada balsam is or is not nearly equal to 1·536 (that of Canada balsam). Thus a section of olivine ($\mu = 1{\cdot}697$) mounted in Canada balsam appears quite rough, with all the unevenness due to the grinding, whereas a section of orthoclase felspar ($\mu = 1{\cdot}526$) appears perfectly smooth; and this affords ready means of distinguishing between the two minerals under the microscope in rock sections.

Some of the liquids convenient for use for this purpose are—

Water	$\mu = 1{\cdot}34$	Clove oil	$\mu = 1{\cdot}54$
Alcohol	1·36	Aniseed oil	1·58
Glycerine	1·41	Almond oil	1·60
Olive oil	1·47	Cassia oil	1·63
Nut oil	1·50	Monobromonaphthalene	1·65

Methylene Iodide $\mu = 1{\cdot}75$

The following is a somewhat similar use of a solid medium.

In the section of an igneous rock, like granite, two minerals, such as quartz and felspar, may be in contact with each other, of which the refractive index of the one (quartz) is known, and that of the other is unknown. Let the junction between the two minerals be viewed by a low power under the microscope; and let the cone of light proceeding from the condenser below the stage be first narrowed, either by employing an iris diaphragm or by lowering the condenser itself; the line of contact will then be very clearly visible if the two minerals differ in their refractive power (Fig. 408). The junction will be rendered even more pronounced if the objective be slightly raised, for a bright band of light will then be seen along the boundary line just within the more refractive mineral. When the objective is slightly depressed the bright band appears just within the less refractive mineral. This effect, whether it be due to total reflection or to diffraction, enables the observer to detect very slight differences of refractive index if the contact be sufficiently well defined. The indices of quartz lie between those of albite and anorthite, so that it is possible by this method to ascertain approximately the refractive index, and therefore the nature, of a plagioclase (*i.e.* a soda-lime felspar) in a rock where it is in contact with quartz.

Fig. 408.

Dispersion.—The light which enters a transparent mineral is differently refracted according to its colour, blue rays being refracted more than yellow, and yellow rays more than red.

Hence a beam of white light becomes separated into the various coloured beams, and these may diverge widely. This character gives rise to the "fire" displayed by certain precious stones. A stone having strong dispersive power converts the incident white light into a beam of coloured lights, whereas a stone of weak dispersive power throws out practically only white light.

The dispersion is usually measured by the difference between the refractive indices for violet and red rays.

	Violet.	Red.	Dispersion.
Thus for Diamond	$\mu = 2{\cdot}465$	2·402	0·063
Rock Crystal	1·564	1·539	0·025
Fluor Spar	1·437	1·431	0·006

The high dispersive power of diamond adds much to its value as a precious stone; the lower dispersion of rock crystal makes this mineral suitable for spectacles, etc.; and the very low dispersion of fluor has led to its employment in "apochromatic" microscope lenses.

Colour.—The superficial colour of minerals is of two sorts, since it may be due (1) to physical causes, *i.e.* to interference, like the colour of mother-of-pearl; (2) to chemical causes, *i.e.* either to the chemical composition of the pure mineral itself or to colouring matter which it contains.

In the first case the colour will vary with the direction in which the surface is viewed.

Colour due to Physical Causes.—As explained on p. 121, when two smooth plates of glass are pressed together bright bands of colour appear between them, due to internal reflection by the intervening film of air. Similar colours are often seen on cracks and flaws in glass or in transparent minerals.

This interference of reflected light plays an important part in some of the optical properties of minerals which have a finely laminar structure, or those which enclose very thin plates or rods of other minerals.

The following terms are used in describing such effects :—

Play of Colours signifies the irregular and shifting flashes of colour, such as impart its peculiar beauty to the precious opal.

Change of Colours signifies the property of exhibiting different colours by reflected light when viewed in different directions, such as belongs to smooth surfaces of labradorite; in this mineral it may be partly due to a finely lamellar structure and partly to inclusions.

Iridescence denotes the broad bands of colour due to the presence within the mineral of curved thin plates (often of air in cracks) of varying thickness, which give rise to a series of different tints.

Opalescence is a peculiar milky appearance observed in the interior of some minerals, notably the translucent varieties of opal.

In "cat's-eye" it takes the form of a single band of opalescent light traversing the mineral in one direction, and has the appearance of being due to a fibrous structure.

Tarnish is a superficial iridescence produced by a deposit upon the surface of the mineral of a fine film of some decomposition product (often an oxide) which gives rise to the colours of thin plates.

Among minerals chalcopyrite is the most conspicuous instance, and the beautifully tarnished specimens of this mineral are commonly known by the name of "peacock copper."

Colour due to Chemical Causes.—The colour-names generally used by mineralogists are those which were drawn up by Werner in the latter half of the eighteenth century. In this scale of colours a distinction is made between the colours of opaque minerals with metallic lustre and those of other minerals. The scale of colours with their various *shades* is as follows :—

Metallic Colours

Red—copper-red.
Yellow—bronze-, brass-, gold-yellow.
Brown—pinchbeck-brown.
White—silver-, tin-white.
Gray—lead-, steel-gray.
Black—iron-black.

Non-Metallic Colours

White—snow-, reddish-, yellowish-, grayish-, greenish-, bluish-, milk-white.
Gray—bluish-, pearl-, reddish-, smoke-, greenish-, yellowish-, ash-gray.
Black—grayish-, velvet-, greenish-, brownish-, reddish-, bluish-black.
Blue—blackish-, azure-, violet-, lavender-, plum-, prussian-, smalt-, indigo-, duck-, sky-blue.
Green—verdigris-, celandine-, mountain-, leek-, emerald-, apple-, grass-, pistachio-, asparagus-, blackish-, olive-, oil-, siskin-green.
Yellow—sulphur-, straw-, wax-, honey-, lemon-, ochre-, wine-, cream-, bay-, pea-, orange-yellow.
Red—aurora-, hyacinth-, brick-, scarlet-, blood-, flesh-, carmine-, cochineal-, rose-, crimson-, peach-blossom-, columbine-, cherry-, brownish-red.
Brown—reddish-, clove-, hair-, chestnut-, yellowish-, wood-, liver-, blackish-brown.

Colour, except in the case of a few minerals, is a character of very little value in the discrimination of species, since most minerals derive their colour from a trace of some impurity which is not essential to the mineral, or from isomorphous intermixture of various compounds.

Fluor spar, for instance, which in its purest state is quite colourless, is more often found tinted with various shades of either green, blue, or yellow, and sometimes red, and one and the same mineral specimen, even the same crystal, may be banded with layers of different colours. Moreover, a mineral in very thin slices, when it is viewed mainly by transmitted light, may present a colour very different from that which it has in the mass when viewed mainly by reflected and dispersed light; black blende, for example, appears brown or even yellow in thin fragments; and the colour of thin fragments of the same mineral may vary largely, owing to the different relative absorptions by different thicknesses of the substance. The above scale is more useful to describe differences of colour than to define any constant character of minerals; but since the estimation of colour varies between different persons, the scale is of little practical use, except when referred to a standard series of minerals such as those exhibited in many large mineral collections.

An attempt to define colour by means of a standard series of pigments has been made in Radde's *Internationale Farben-skala*, which is sometimes referred to by mineralogists.

Streak.—A mode by which colour is made of real value in the discrimination of species consists in observing the colour, not of the mineral as it ordinarily occurs, but of its powder, so that any variations due to structure or thickness are eliminated. The colour of the powder, or the

"streak" of the mineral, is a feature of some constancy. A distinction was formerly made between the "streak," the term being then employed to denote the colour of the scratch made upon a mineral by an edge of some harder substance, and the "colour of the powder," as seen upon a white surface; in this sense, however, the streak was merely the colour of the powder as seen upon the mineral itself. The only systematic method of observing the streak consists in scratching off a little powder or a small fragment from the mineral and crushing and flattening it with the blade of a knife upon a sheet of white paper, or, better, upon a piece of unglazed porcelain. A soft mineral may be rubbed directly upon the porcelain. The streak so obtained is sometimes very different from the colour of the mineral, and is a more constant character than the latter.

The streak is especially valuable in distinguishing between the opaque metallic minerals, in which other optical methods are not available, and which are too heavy to be tested by heavy liquids. Thus iron pyrites and copper pyrites are somewhat similar in appearance, but the streak of the former is much lighter than that of the latter, and this character, combined with the hardness, is quite sufficient to distinguish the two species.

Phosphorescence.—Some minerals become luminous at a temperature far below that of red heat, either by friction, by heat, by previous exposure to light, or by chemical actions; such minerals are said to phosphoresce. Diamond and some varieties of fluor, if exposed to sunlight and then taken into a dark room, appear strongly luminous; quartz becomes luminous by friction with quartz; mica emits flashes of light when cleaved; the same feature is observed in potassium chloride during crystallisation; and some varieties of fluor phosphoresce when raised to a temperature less than that of boiling water.

This property was known in the diamond in very early times, and at the beginning of the seventeenth century it was discovered by Cascariolo of Bologna that barytes becomes phosphorescent after ignition with charcoal (owing to the formation, as is now known, of barium sulphide).

Phosphorescence is most beautifully shown when the substance is enclosed in a vacuum tube and exposed to the electric discharge of a Ruhmkorff coil; diamond, blende, and other phosphorescent minerals are by this process made to glow with a brilliant light.

The colour of the light emitted by a phosphorescent mineral which has been, for example, exposed to sunlight, varies with the nature of the mineral and also with the temperature at which the observation is made. But the effect is always temporary; after a few hours (as in the case of calcium sulphide), minutes, or seconds (as in the case of aragonite), the substance ceases to glow, until it has been again subjected to the influence which excites the phosphorescence.

The property of phosphorescence consists, then, in the power possessed by certain substances of transforming energy communicated to them by one of the above methods into visible radiations, and continuing to do so, after the exciting agent has ceased to operate.

It is always found that when this energy has been communicated in the form of light rays, the rays emitted have a greater wave length than those received.

Fluorescence.—The same general features belong to the property known as fluorescence.

Some crystals of fluor, when examined in sunlight, possess a peculiar milky or hazy appearance which only extends to a slight depth below the surface, and diffuse a bluish or greenish light from this superficial layer; even the ultra-violet or non-luminous rays of the solar spectrum are capable of exciting fluorescence in such crystals.

Here, again, the rays which are received by the mineral are transformed within its substance, and are emitted as diffused light of greater wave length so long as the mineral is illuminated.

As a result of this property the light transmitted by a fluorescent mineral is of a different colour from that which is diffused from its surface. Some of the purple fluor of the North of England, if viewed by transmitted light, appears green.

Little is known of the cause of this effect. In the fluorescent amber of Sicily it is said to be connected with the presence of a vast number of microscopical cavities.

4. **Other Characters—Magnetism.**—Except in so far as it is studied in connection with the symmetry of crystals, magnetism is not a property of much theoretical or practical importance in mineralogy, since very few minerals possess the property to a marked extent. Magnetite, which was formerly known under the name of the lodestone, and in which the magnetic character was originally discovered, is the only mineral which exhibits "polar" magnetism in any degree. Pieces of magnetite frequently possess a north and south pole, one of which repels, and the other attracts, the north pole of a magnetic needle; this property only belongs in a far less degree to a few other minerals, such as pyrrhotite and platinum. Ordinary magnetism, which is the power of attracting either pole of the needle, or of being attracted, like iron, by either pole of a strong magnet, is a property of several minerals containing iron; many ferriferous minerals which are not magnetic can be made so by fusion, owing to the formation of magnetic oxide of iron, so that the property is also of importance in the examination of minerals by the blowpipe.

Electricity.—Like other substances, minerals become electrified by friction; among those which are non-conductors of electricity, and upon which consequently this property may be observed without insulating the mineral, may be mentioned quartz, which becomes positively electrified, and sulphur, which becomes negatively electrified, by friction with such substances as cloth or wool.

The minerals which are good conductors of electricity are the metals, and many of the minerals possessing metallic lustre.

When two different minerals, both conductors of electricity, are placed in contact and made to form part of a conducting circuit, and are heated or cooled at their surface of contact, a thermo-electric current passes from

the one to the other; this property, which is very marked when the two substances chosen are antimony and bismuth, is of importance as a possible cause of currents, which may circulate in metallic veins and give rise to decomposition and recomposition of minerals.

For the thermo-electricity of pyrites, see p. 326.

CHAPTER II

THE DETERMINATION OF MINERALS

In order to determine the nature of a mineral with certainty and to fix its place in the system, if it be a new compound, nothing is satisfactory save a complete quantitative analysis, combined with a measurement of the crystal angles and of the physical constants.

In general, however, the specimen under examination belongs to a known species whose properties have been more or less completely determined, and it is only necessary to ascertain to which of the known species it is to be referred.

For this purpose it is in general sufficient to prove that it corresponds with some well-determined mineral both in its chemical reactions and in its crystalline form. To determine the crystalline form with certainty some of the physical properties must also be examined, especially, if possible, the optical characters in parallel and convergent light; even if the crystals cannot be measured the optical characters in themselves are often decisive. The most valuable confirmatory evidence is supplied by the specific gravity.

In order to use as little of the material as possible it is highly advisable to apply physical tests first, since they involve scarcely any destruction of the mineral.

For the same reason, when chemical tests are subsequently applied, the first should be such as can be effected by the blowpipe and by reactions on a minute scale viewed under the microscope.

Further, it is extremely important that the chemical characters should be determined upon the *very material* which has been used for the physical examination; if this be not done there is no certainty that the two sets of properties really belong to the same substance.

1. **Physical Examination.**—Except after long experience among minerals the external aspect of a specimen is of little value as an aid to its determination. Only in one respect is the appearance of a mineral of real use; if it possesses metallic lustre it is probably either a metal or belongs to the class of metallic minerals; *i.e.* the sulphides (including arsenides and selenides) or the sulpharsenites (including sulphantimonites and sulphobismuthites). This is a useful guide and a great help in determinative mineralogy. The great class of silicates have, for the

most part, a vitreous lustre; so also have many of the carbonates and sulphates.

The metallic minerals are usually nearly opaque, hence optical examination is with them generally impossible; but the streak should be noted, and chemical tests (especially reduction on charcoal) should then be at once applied to them.

But if a mineral be transparent it should before all things be examined in the polarising microscope in the following manner:—A small fragment, having been placed in a drop of oil or water on a glass slide, is broken with the blade of a knife; this gives at once some idea of (1) the hardness of the mineral, (2) its cleavage; and the drop of liquid prevents any of the fragments flying away during fracture. Viewed under the microscope the clearness of outline and visibility of the surface will indicate whether the fragments have a refractive power near that of the liquid or widely different from it.

The polariser is then inserted and the presence or absence of dichroism is noted.

The analyser being next inserted, and care being taken that the nicols are crossed, it can at once be seen whether the mineral is isotropic or not. If it possesses birefringence, the extinction angles of the cleavage flakes or of crystalline faces (if they are sufficiently large or characteristic to be identified) should be measured. For this purpose the crystals or cleavage fragments should be turned over in the drop and viewed in different directions. Compensation with the quartz wedge will give some measure of the birefringence, and, if the crystals be needles, will show (as described on p. 175) whether they are elongated in a positive or negative direction; *i.e.* whether the axis of the needle is the vibration direction corresponding to the greatest index of refraction or to the least.

Finally, the fragments, being immersed in a drop of oil, are to be examined in convergent light with an immersion objective, and the interference phenomena observed. It will in general be necessary to hunt among the fragments for one which shows the optic axis or axes, and to turn it about with the point of a needle into an appropriate position. For this purpose viscid cedar oil will be found a very convenient medium.

In the course of the microscopic examination much will have been learnt regarding the mineral, whether it is isotropic, uniaxial, or biaxial, or pseudo-symmetric, whether it is simple or twinned; an estimate will have been formed of its refraction and birefringence, and of the sign of the latter, also of the axial dispersion. The optic axial angle may even be approximately measured by noting the number of divisions which the interval between the axes occupies on an eye-piece micrometer which has been previously calibrated by means of known sections.

It is most important also to note, with a view to the subsequent chemical examination, whether the mineral is pure or contains inclusions.

A fragment can then, if the mineral be not too heavy, be dropped

into a heavy liquid and the specific gravity determined as explained on p. 192.

If the material is very heavy it may be expected to contain lead or one of the other heavy metals; the lead compounds often possess also a rather greasy or resinous lustre.

If crystals with plane faces are available they should be measured with the goniometer, special care being taken to identify the faces through which optic axes are visible and those whose extinction angles have been ascertained.

Measurements should also be made of the refractive index (if it is sufficiently low) by means of the total reflectometer, provided that a sufficiently large plane crystal face or cleavage surface can be found.

If a crystal has been measured, its optical properties ascertained, and if measurements have also been made of the specific gravity and refractive index, it will often be found that sufficient *numerical* data have been obtained for the identification of the mineral, by means of the tables on pages 551 to 561; a few simple chemical tests will then suffice as a qualitative confirmation.

In many cases, however, it is necessary to know something about the composition before even a guess can be made as to the species.

2. **The Chemical Examination.**—For the practical determination of minerals, when it is only required to refer a specimen to some known species, the methods of quantitative analysis are not necessary; simple qualitative tests, combined with the physical and crystalline characters of the mineral, are generally sufficient to distinguish one species from all the others.

The tests applied are of two sorts:—

(*a*) *Pyrognostic Examination, or Dry Tests.*—The mineral is heated either in a closed or open tube or upon charcoal, aluminium or platinum, for the purpose of fusion, sublimation, oxidation, or reduction; or else it is fused with fluxes for the purpose of obtaining the characteristic (coloured) products which are yielded by certain elements.

(*b*) *Solution Reactions, or Wet Tests.*—The mineral is subjected to the action of various solvents, generally water or acids; the resulting solutions are tested with reagents, and the precipitates produced are distinguished by their colours and solubilities according to the ordinary methods of qualitative analysis.

Since the results of qualitative analysis are not expressed numerically, they lack the precision of physical and crystallographic methods; it is therefore very important to check the chemical examination by the use of *comparative tests.* The reactions of the mineral examined should be carefully compared with the same tests applied to the same quantity of an undoubted sample of the mineral species to which it is referred, or of minerals which it resembles.

As the most important of all preliminary chemical tests, a mineral should first be treated with a drop of hydrochloric acid, when effervescence will denote the presence of a carbonate, and the evolution of hydrogen sulphide a sulphur compound.

(*a*) Pyrognostic Reactions

Fusion and Volatilisation.—Most minerals when heated pass more or less readily into the liquid state. Some fuse at a high, and some at a low temperature, and it is often possible to distinguish between minerals which have nearly the same appearance by observing their relative temperature of fusion. For this purpose a small splinter of the mineral is held in a platinum forceps and the blowpipe flame is directed upon its edge. Some minerals, such as (1) stibnite and (2) natrolite, fuse readily to a globule, the former even in a candle flame; (3) almandine garnet fuses with greater difficulty; (4) actinolite and (5) orthoclase only become rounded on thin edges; (6) bronzite shows only slight traces of fusion even in very thin splinters, while (7) quartz is infusible before the ordinary blowpipe.

Upon these seven species von Kobell founded a scale of fusibility. A mineral, for example, which fuses more readily than actinolite but less readily than almandine is said to have a fusibility between 3 and 4; one which in this respect lies between orthoclase and bronzite is said to have a fusibility between 5 and 6.

This scale is usually given in tables for the determination of minerals; in reality, however, the intervals between its successive members correspond to very unequal differences of temperature. Penfield uses chalcopyrite in place of natrolite for 2.

Since it is generally impossible to determine the actual temperature of fusion, it is preferable to ascertain merely whether the mineral is fusible with ease or difficulty, or for the purposes of diagnosis to determine whether it is more or less fusible than the minerals with which it might be confounded.

No minerals are, in reality, absolutely infusible when subjected to such temperatures as those of the oxyhydrogen flame or the electric arc; but many—especially silicates—are infusible in the flame of the ordinary mouth blowpipe.

In testing fusibility the oxidising flame should be used. During fusion the properties of the mineral are usually changed. Those containing water often intumesce, or spit; those which yield gases may become slaggy or may decrepitate. Minerals containing much iron generally fuse to a magnetic globule, owing to the formation of magnetic oxide of iron.

Colour imparted to Flame.—When held in the non-luminous flame of a Bunsen burner, minerals which contain certain volatile elements impart characteristic colours to the flame. The reaction is often made more apparent by previously moistening the mineral with hydrochloric acid, which may combine with some of the metals to form volatile chlorides. The colours imparted to flame should be observed at the same time with the fusibility. They are given in Table A (p. 548).

The colours may be completely masked when the mineral contains enough sodium to give a very pronounced yellow flame.

During this process the smell given off should be observed and compared with the list in Table D (p. 549).

Sublimation—Heating in Closed Tube.—When the mineral is heated in a glass tube (formerly called a matrass) closed at the lower end (which may be conveniently in the form of a bulb) any condensible vapours which are given off will be deposited as a sublimate upon the cool sides of the tube. For this purpose a small portion of the mineral is powdered or broken into minute fragments before being introduced into the tube. Any changes of colour which take place as the sublimate cools should be noted. The characteristic sublimates are given in Table B (p. 548).

Oxidation—Heating in Open Tube.—When the powdered mineral is heated in a glass tube open at both ends and held in a slanting position, so that a free current of air can rise through it, oxidation products are yielded, which may either be deposited as sublimates, or may issue as characteristic vapours.

The sublimates are given in Table C (p. 549).

The vapours are given in Table D (p. 549).

Reduction—Heating on Charcoal, etc.—Many metallic oxysalts may be deprived of their oxygen by fusion upon charcoal either alone or mixed with sodium carbonate, when certain incrustations and other fusion products are produced; the former are generally oxides having characteristic colours; the latter are often fusible metals.

For this purpose the mineral is to be powdered and intimately mixed with about four times its bulk of sodium carbonate; slightly moistened with water; and heated before the reducing flame of the blowpipe in a cavity scooped out of a charcoal support. The characteristic incrustations are given in Table E (p. 549).

When metallic particles are produced they serve to confirm and distinguish these determinations, and also to reveal the presence of copper, lead, gold, etc. If a very minute quantity of the mineral be employed the metallic bead is best observed by breaking up the fused mass in a little water and washing off the suspended charcoal; the sodium carbonate is dissolved and the glittering metallic particles are then easily detected and examined. They may be any of those given in Table F (p. 550).

These globules may be dissolved in acid or aqua regia and tested by the ordinary methods of qualitative analysis.

During fusion on charcoal the smell should be observed; the indications will be those of Table D. If there is an infusible residue it should be treated with cobalt nitrate; see Table K (p. 551).

Fusion with Fluxes—Borax Bead.—When borax is heated with minerals containing certain metallic elements it decomposes them and combines with the oxides of these metals to form glassy compounds having characteristic colours.

For this purpose the borax is fused before the blowpipe in a small loop of platinum wire to a transparent bead; a very minute portion of the powdered mineral is then brought into contact with the bead after slightly moistening it with water, and the bead is again fused until the mineral is completely dissolved.

Sulphides, arsenides, etc., must first be reduced to the condition of oxides by roasting.

The colours imparted to the bead by exposure to the oxidising and reducing flames of the blowpipe are then observed. They may be one or more of those mentioned in Table G (p. 550).

Microcosmic Salt Bead.—The treatment in the bead of microcosmic salt is the same as with borax. The colours are for the most part the same as those of the borax bead. The particulars in which they differ are given in Table H (p. 550).

Treatment with Cobalt Nitrate.—Infusible minerals, after being heated, are to be moistened with solution of cobalt nitrate and ignited in the oxidising flame; this may impart to the mineral one or more of the characteristic colours given in Table K (p. 551).

This treatment is especially valuable as a test for aluminium and zinc; it should always be applied to any infusible residue obtained by heating the mineral on charcoal.

(*b*) Solution Reactions.

Solution.—All minerals are more or less soluble in certain solvents: in order to examine the soluble portion, the acids and bases which the solution contains are separated from one another and determined by the precipitates produced by appropriate reagents. The solvents employed are water, acids (hydrochloric, nitric, sulphuric, hydrofluoric, and aqua regia), and alkalies (potash, soda, ammonia). The mineral is first to be pulverised.

Many minerals are only partially soluble in one or more of these solvents, being decomposed by them, sometimes with evolution of a gas, and sometimes with formation of a residue; many are only very slightly attacked, and only after very long heating with the solvent.

In testing a mineral with acid solvents first the dilute and then the concentrated acid should be employed.

It will be found that among the minerals soluble in water are all the simple compounds of the alkaline metals; many sulphates containing these metals along with others; all the nitrates—but not the basic sulphates; few oxides; no sulphides or sulphosalts; no silicates.

Partially soluble with a residue are many double salts, *e.g.* gaylussite, from which the sodium carbonate is dissolved out.

It appears further that among the minerals completely soluble in HCl are to be found some manganites and all the carbonates (except cerussite).

The carbonates give off CO_2 with effervescence; the sulphides give off H_2S, which blackens filter paper moistened with lead acetate.

The insoluble minerals are usually fused with sodium carbonate, and treated first with water and then with hydrochloric acid. The portion of the fused mass soluble in water contains the acid radicles as sodium salts; the portion dissolved in hydrochloric acid contains the bases in the form of chlorides.

The Testing of Solutions (either of the minerals themselves or of their soluble products after fusion, etc.)—The majority of minerals are complex compounds containing more than one basic radicle and often more than one acid radicle. These are to be separated from each other as insoluble precipitates in the usual manner; all the elements present in a complicated mineral may be discovered with greater certainty in the solutions than by pyrognostic methods alone, because they can be more effectively separated. The steps indicated are used to ascertain —firstly, to which of the great mineral groups the substance belongs, by the determination of its predominant acid radicle; secondly, what are its basic elements. Each determination is to be checked by one or more of the pyrognostic tests. The chromates, arsenates, carbonates, sulphides, arsenides and sulphosalts will have been already detected by these tests.

Microchemical Reactions.—Some solution-reactions give rise to crystallised precipitates whose form is so characteristic that they may be recognised under the microscope.

For this purpose a drop of the solution is placed on a microscope slide and brought into contact with a drop of the reagent placed close to it. If the solutions are sufficiently dilute the precipitate crystallises slowly and in distinct crystals. The chief advantage of microchemical methods is the minute amount of material required; in fact a number of the reactions mentioned above may be effected under the microscope with a mere grain of the mineral; and the processes of solution, evaporation, and precipitation may, with a little practice, be carried on upon the microscope slide instead of in a test-tube or beaker. Even filtration may be successfully effected by a slip of filter paper, which carries off a drop of solution and leaves the solid residue behind.

But it will be sufficient here to confine our attention to a few of those reactions which yield crystals of typical form easily recognisable by their appearance and optical properties, especially those reactions which indicate elements difficult to determine by the preceding methods, such as Al, Si, Ca, U, K, Cs, Na.

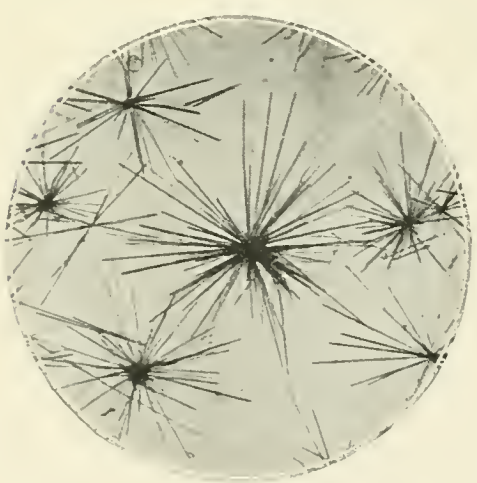

Fig. 409.—Microchemical Gypsum.

Calcium.—One of the best and most typical precipitates is that of gypsum, produced (for example) by very dilute sulphuric acid mingling with a drop of solution of a calcium salt (Fig. 409). Careful examination shows that these crystals possess the characteristic form of the mineral gypsum; some are simple tablets; some are arrow-head twins; and they have an extinction angle of 52° viewed through (010).

This is by far the most sensitive reaction known for calcium, as also for sulphuric acid.

Magnesium.—A rare mineral of organic origin belonging to the hemimorphite class in the orthorhombic system (p. 62) is struvite, $NH_4MgPO_4 . 6H_2O$. The typical form of this mineral is shown in Fig. 410, which represents one of the crystals from Hamburg, to be seen in most mineral collections. If to a drop of dilute solution of a magnesium salt containing sal-ammoniac and ammonia a drop of sodium phosphate be added, typical struvite crystals soon separate (Fig. 411). They come down most readily in a warm solution.

Fig. 410.—Struvite.

Ammonium.—The same test is used for the detection of ammonium. To the solution of the ammonium salt a drop of sodium phosphate, one of soda, and one of magnesium sulphate are added in succession. Struvite crystals, as before, come down on warming. This precipitate may also be used as a test for phosphoric acid.

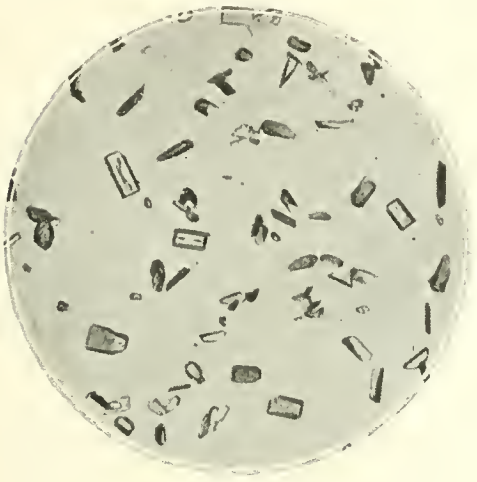

Fig. 411.—Microchemical Struvite.

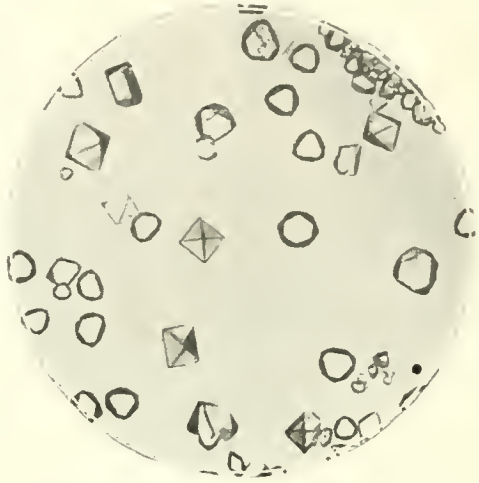

Fig. 412.—Microchemical Cæsium Alum.

Aluminium.—Solutions of aluminium salts in sulphuric acid give, with cæsium sulphate, colourless isotropic octahedra of cæsium alum (Fig. 412).

Cæsium is detected by the same reaction when aluminium sulphate is added to a solution of a cæsium salt.

Sodium.—Uranyl acetate gives with sodium salts yellow isotropic tetrahedra of a uranyl-sodium acetate (Fig. 413). Care must be taken that the reagent is itself free from sodium, which is easily detected by the spectroscope if present in the minutest traces.

Uranium is detected by the same reaction. A solution in nitric acid is saturated with soda and treated with acetic acid.

Silicon.—Silicates are to be decomposed with hydrofluoric acid in a platinum dish; some of the silicon fluoride given off is collected in a drop of water on the under side of the dish cover. The addition of a potassium salt to this gives clear colourless isotropic cubes of K_2SiF_6.

Potassium is detected by the yellow octahedra of K_2PtCl_6 produced on addition of solution of platinum tetrachloride to dilute solutions of potassium salts in hydrochloric acid.

Similar characteristic reactions can be employed for a number of

other elements, but for most of them the blowpipe or one of the reactions mentioned in the previous section are equally easily and quickly applied. Thus it is unnecessary to resort to a microchemical test for lead or copper, since these metals are so easily recognised by reduction on charcoal.

It is only when the amount of available material is excessively minute that the observer is driven to rely entirely upon microchemical

Fig. 413.

tests; and then many of his experiments will be simply the solution reactions described above or similar reactions modified in such a way as to be applied on a very small scale under the microscope.

For example a minute trace of chloride in a drop of dilute solution can be detected by the production, with silver nitrate, of a white precipitate soluble in ammonia; the microscope further shows that the precipitate of silver chloride is redeposited from the ammoniacal solution in isotropic octahedra.

Again, a minute trace of nickel in a very dilute solution is detected by the rose coloration produced when it is brought into contact with a drop of sodium sulphocarbonate.

Spectroscopic Examination.—The most delicate of all tests for elements which are only present in traces is, of course, the spectrum which some of them give when a volatile compound containing the element is heated in the flame of a Bunsen burner.

A small fragment of the mineral moistened with hydrochloric acid, or mixed with ammonium fluoride and sulphuric acid, is brought on the end of a clean platinum wire into the edge of the flame, which is then observed with a small direct-vision spectroscope.

The following elements may be at once detected if the compound is at all pure:—

Sodium by its brilliant yellow line.

Lithium by two lines, one a weak yellow, and the other a bright red.

Cæsium by two bright blue lines.

Rubidium by two characteristic violet lines, and by two in the red (which must not be confused with that of potassium).

Potassium by a characteristic line in the extreme red and one in the extreme violet.

Thallium by a single brilliant green line.

Calcium by a brilliant green line and a brilliant orange line.

Strontium by a blue line and a series of brilliant lines in the red and orange.

Barium by a series of brilliant green and red lines.

Indium by a blue and a violet line.

These lines are all very characteristic, but since minerals are scarcely ever pure simple compounds they may contain several of the above and other elements together, so that the spectra yielded by the minerals may be complicated and may mask each other. The spectroscopic test is, therefore best applied to the comparatively pure precipitates or solutions obtained in the chemical examination of the mineral rather than to the mineral itself; it is of incomparable value in detecting minute traces of these (and, in skilful hands, of many other) elements.

Very interesting and characteristic spectra are also obtained by subjecting small fragments of most conducting minerals to the electric spark discharge.

Absorption Spectra.—Some minerals, when examined at ordinary temperatures with the spectroscope by transmitted light, show dark absorption bands due to the elements which they contain.

Many of the minerals containing didymium, for example, show broad black bands in the red and green which are characteristic of that element (parisite, bastnäsite, monazite).

If the mineral is sufficiently transparent the bands can even be seen by simply allowing direct sunlight to fall upon the specimen and viewing it with the spectroscope; the reflected light will have penetrated sufficiently far into the mineral to show the absorption spectrum. Thus crystals of monazite, (Ce, La, Di)PO_4, can be at once recognised by mere inspection with the spectroscope. If one of the specimens from the Binnenthal, for example, on which isolated crystals of monazite are

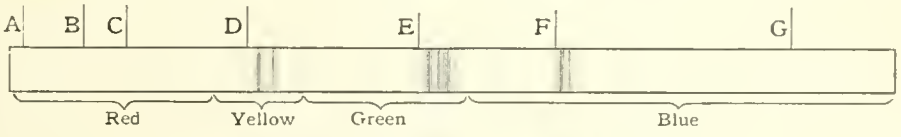

Fig. 414.—Absorption spectrum, Monazite.

associated with anatase upon quartz and albite, be viewed through a spectroscope in direct sunlight, the characteristic didymium bands flash into the spectrum the instant a crystal of monazite comes opposite to the slit (Fig. 414).

The mineral rhabdophane, which was formerly supposed to be blende, was discovered in this way and was named from this property. The carbonate of cerium (etc.), parisite, also shows such bands.

If a very small fragment of the mineral is to be examined it will be found advisable to place it on the stage of a microscope and focus the direct rays of the sun upon it by means of the substage condenser; the eye-piece may then be removed and replaced by the direct-vision spectroscope.

Such absorption spectra are especially characteristic of the metals of the Ce, La, Di group.

Two quite common minerals also show characteristic absorption spectra, namely zircon and the variety of garnet known as almandine.

Fig. 415 represents the absorption spectrum of zircon.

Fig. 416 represents the absorption spectrum of almandine.

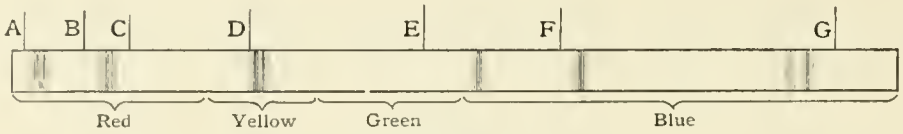

Fig. 415.—Absorption spectrum, Zircon.

This test is especially useful in the case of gemstones, since it may be applied without the necessity of sacrificing any of the material or even of unmounting the stone. A clue to the composition may thus be obtained by merely looking at the stone through a spectroscope.

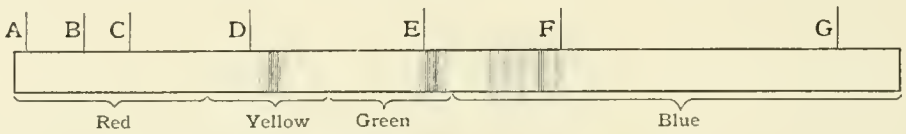

Fig. 416.—Absorption spectrum, Almandine.

It must be remembered that, like all the directional properties, the absorption spectrum is different for rays which vibrate in different directions within the crystal. This may be very easily seen by placing a minute crystal of the hexagonal mineral parisite (a carbonate and

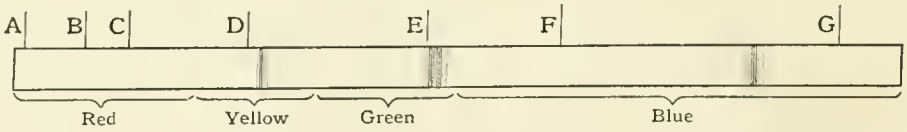

Fig. 417.—Absorption spectrum of ordinary ray, Parisite.

fluoride of Ce, La, Di, Ca) lengthwise under the microscope, and allowing the incident light to pass through the polariser.

When the axis of the crystal is parallel to the longer diagonal of the polariser, the spectrum due to the ordinary rays is that shown in Fig. 417.

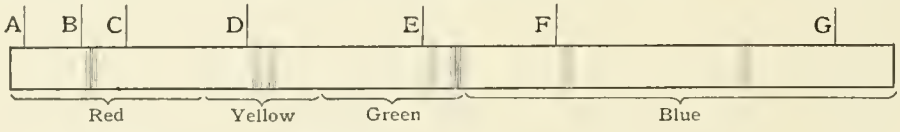

Fig. 418.—Absorption spectrum of extraordinary ray, Parisite.

When the crystal is turned through 90° the spectrum is that of the extraordinary rays, Fig. 418.

The changes which the spectrum undergoes with a change of direction are, like the spectrum itself, characteristic of the substance.

Throughout the whole process of testing a mineral it must be remembered, especially with the delicate tests of the flame reactions and of the spectroscope, that the effects produced may be due not to the mineral itself but to other substances inclosed in it. Nothing can therefore be more important than to ascertain first, by means of the microscope, the purity of the specimen and the nature of the inclosed mineral, and if possible to remove the latter either by picking it out under the microscope from the crushed material or by separation by means of a heavy liquid, if the two minerals differ in specific gravity.

Further, the reactions may be partly due to a slight intermixture of an isomorphous compound which cannot be seen or separated by any mechanical process, since it is present as one of the constituents of a solid solution.

For the chemical identification of a mineral, attention must be paid rather to its main constituents than to those which it contains as mere traces, and this fact robs the spectroscopic tests of some of their value in practice. A useful hint is often supplied by the minerals with which the doubtful material is associated or by its products of decomposition; green malachite or blue chessylite, for example, encrusting the mineral, indicate copper, while the apple green of nickel or the rose red of cobalt compounds may often be detected on the decomposed surface of a mineral containing either of these elements.

Some well-known minerals possess such characteristic properties that they may be recognised at once.

If powerfully magnetic, the specimen is certainly magnetite; the only other markedly magnetic minerals are pyrrhotite and platinum, and these are only weakly so in comparison with magnetite. Ilmenite is slightly magnetic.

Again, rock-salt is at once recognisable by its taste; the astringent taste of the alums and of the sulphates of iron and of copper, and the bitter taste of epsomite are also characteristic. Only minerals which are soluble in water possess a taste.

No minerals have in themselves a smell sufficient to distinguish them, but the hydrated silicates of alumina belonging to the family of the clays emit a characteristic earthy smell when breathed upon; and some minerals which contain sulphur emit a sulphurous smell when struck with a hammer.

Some clays and allied minerals adhere to the tongue when touched with it; this property affords a rough method of distinguishing between steatite and lithomarge, of which only the latter adheres to the tongue. One variety of halloysite possesses this property in so marked a degree that it has been named glossecollite.

The remarkable greasy feel of steatite is also of some value in its recognition.

Many copper compounds are blue or green; most uranium compounds are brilliant green or yellow.

APPENDIX I

THE THIRTY-TWO CLASSES OF CRYSTALS

Axes of crystalline symmetry are of four sorts, namely, digonal, trigonal, tetragonal, hexagonal. All the parts of the crystal are brought into the position previously occupied by equivalent parts, by a rotation of—

180°	about a	digonal axis
120°	,,	trigonal ,,
90°	,,	tetragonal axis
60°	,,	hexagonal ,,

Hence, if there be another axis of symmetry inclined to an n-gonal axis, there must be n such axes ; or if there be a plane of symmetry inclined to the n-gonal axis there must be n such planes.

The above axes, together with the plane of symmetry and the centre of symmetry, constitute the six elements of symmetry possible in crystals.

An n-gonal axis may be accompanied simply by axes of digonal symmetry perpendicular to it (without planes of symmetry) ; the symmetry is then called holoaxial : *e.g.* the trigonal axis of quartz (Fig. X.).

An n-gonal axis may be the intersection of planes of symmetry ; the symmetry is then called di-n-gonal : *e.g.* the ditrigonal axis of tourmaline (Fig. XII.).

An n-gonal axis may be perpendicular to a plane of symmetry ; the symmetry is then called equatorial : *e.g.* the tetragonal axis of scheelite (Fig. XXIV.).

An n-gonal axis may operate simultaneously with an equatorial plane (as explained on p. 36) : the symmetry is then called alternating : *e.g.* the hexagonal axis of dioptase, (Fig. XV.) or the dihexagonal axis of calcite (Fig. XIX.).

An n-gonal axis which is perpendicular neither to a plane of symmetry, nor to an axis of even symmetry, is called polar.

By applying the above considerations to the four sorts of axes, the first twenty-seven classes of symmetry can be at once deduced. The remainder are found by considering how two or more axes of symmetry can be combined ; three tetragonal or three digonal axes can be equally inclined to a trigonal axis, and in that case involve the presence of three more trigonal axes. This leads to the cubic system, which is characterised by four trigonal axes, or, as it may be called, "tesseral symmetry." Any other combination which may be devised of the elements of symmetry possible in a crystal will be found to be identical with one of those already obtained.

In the following figures, I.–XXXII., each class is represented by the simplest prism which belongs to it ; the order of the principal axis, and consequently the system, is at

once seen from the character of the prism. The true symmetry of each class is indicated by the form and disposition of an etched figure ; and a comparison of the various figures shows how the same form may occur in all the classes of a system and be distinguished by etching ; any substance belonging to the cubic system may crystallise in cubes, and any belonging to the tetragonal system may crystallise in square prisms.

(unsymmetrical) denotes the etching on a face which is not perpendicular to a plane or axis of symmetry.

(symmetrical about a centre) denotes the etching on a face perpendicular to a digonal axis.

(symmetrical about two lines) denotes the etching on a face perpendicular to a di-digonal axis.

denotes the etching on a face perpendicular to a tetragonal or di-tetragonal axis.

Column II. gives the name of the most general form $\{hkl\}$ characteristic of each class, *i.e.* the form obtained by repeating a plane about the elements of symmetry given in column I. Most authors now name the classes after these forms ; for example, class X. is called the trigonal trapezohedral class, class XXVIII. the tetrahedral-pentagonal-dodecahedral class.

The whole system of classes can easily be recovered by considering the possible cases in the order given below :—

1. No symmetry ; 2. centre of symmetry ; 3. plane of symmetry ; 4–8. a digonal axis ; 9–13. a trigonal axis ; 14–20. a hexagonal axis ; 21–27. a tetragonal axis ; 28–32. four trigonal axes.

In each case the characteristic axis may be polar, alternating, holoaxial, or equatorial, and each such axis may be n-gonal or di-n-gonal. It must be noticed, however, that a di-n-gonal axis cannot occur in holoaxial crystals, since it involves planes of symmetry.

System.	I. Symmetry of the Class.	II. Name of the General Form $\{hkl\}$.	Figure.	Example.
Anorthic	I. No symmetry	Pedion	Fig. I.	1. *Calcium hyposulphite.*
	II. Centre of symmetry	Pinakoid	Fig. II.	2. *Axinite.*
Monoclinic	III. Plane of symmetry	Dome	Fig. III.	3. *Clinohedrite.*
	IV. Digonal polar	Sphenoid	Fig. IV.	4. *Tartaric acid.*
	,, alternating = II.			
	V. ,, equatorial	Prism	Fig. V.	5. *Gypsum.*
Orthorhombic	VI. ,, holoaxial	Rhombic bisphenoid	Fig. VI.	6. *Sulphur.*
	VII. Di-digonal polar	Rhombic pyramid	Fig. VII.	7. *Hemimorphite.*
	,, alternating = V.			
	VIII. ,, equatorial	Rhombic bipyramid	Fig. VIII.	8. *Barytes.*
Hexagonal	IX. Trigonal polar	Trigonal pyramid	Fig. IX.	9. *Sodium periodate.*
	,, alternating = XI.			
	X. ,, holoaxial	Trigonal trapezohedron	Fig. X.	10. *Quartz.*
	XI. ,, equatorial	Trigonal bipyramid	Fig. XI.	11.
	XII. Ditrigonal polar	Ditrigonal pyramid	Fig. XII.	12. *Tourmaline.*
	,, alternating = XIII.			
	XIII. ,, equatorial	Ditrigonal bipyramid	Fig. XIII.	13.
	XIV. Hexagonal polar	Hexagonal pyramid	Fig. XIV.	14. *Nepheline.*
	XV. ,, alternating	Trigonal rhombohedron	Fig. XV.	15. *Dioptase.*
	XVI. ,, holoaxial	Hexagonal trapezohedron	Fig. XVI.	16. *Barium stibiotartrate*
	XVII. ,, equatorial	Hexagonal bipyramid	Fig. XVII.	17. *Apatite.* [+*pot. nitr.*
	XVIII. Dihexagonal polar	Dihexagonal pyramid	Fig. XVIII.	18. *Greenockite.*
	XIX. ,, alternating	Ditrigonal scalenohedron	Fig. XIX.	19. *Calcite.*
	XX. ,, equatorial	Dihexagonal bipyramid	Fig. XX.	20. *Beryl.*
Tetragonal	XXI. Tetragonal polar	Tetragonal pyramid	Fig. XXI.	21. *Wulfenite.*
	XXII. ,, alternating	Tetragonal bisphenoid	Fig. XXII.	22.
	XXIII. ,, holoaxial	Tetragonal trapezohedron	Fig. XXIII.	23. *Strychnine sulphate.*
	XXIV. ,, equatorial	Tetragonal bipyramid	Fig. XXIV.	24. *Scheelite.*
	XXV. Ditetragonal polar	Ditetragonal pyramid	Fig. XXV.	25. *Iodosuccinimide.*
	XXVI. ,, alternating	Tetragonal scalenohedron	Fig. XXVI.	26. *Chalcopyrite.*
	XXVII. ,, equatorial	Ditetragonal bipyramid	Fig. XXVII.	27. *Zircon.*
Cubic	XXVIII. Tesseral polar	Tetrahedral pentagonal dodecahedron	Fig. XXVIII.	28. *Ullmannite.*
	XXIX. ,, holoaxial	Pentagonal icositetrahedron	Fig. XXIX.	29. *Cuprite.*
	XXX. ,, central	Dyakis dodecahedron	Fig. XXX.	30. *Pyrites.*
	XXXI. Ditesseral polar	Hexakis tetrahedron	Fig. XXXI.	31. *Tetrahedrite.*
	XXXII. ,, central	Hexakis octahedron	Fig. XXXII.	32. *Galena.*

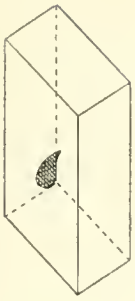

Fig. I.
Asymmetric.

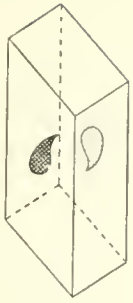

Fig. II.
Centro-symmetrical.

Fig. III.
Equatorial.

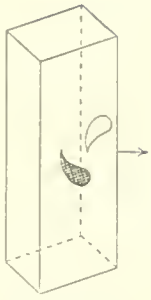

Fig. IV.
Digonal Polar.

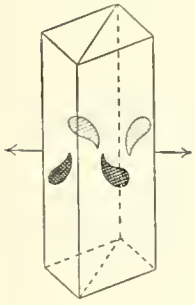

Fig. V.
Digonal Equatorial.

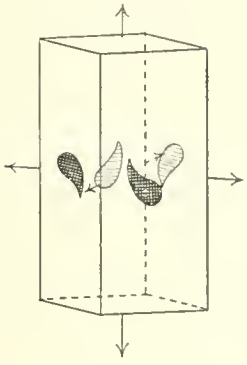

Fig. VI.
Digonal Holoaxial.

Fig. VII.
Di-digonal Polar.

Fig. VIII.
Di-digonal Equatorial.

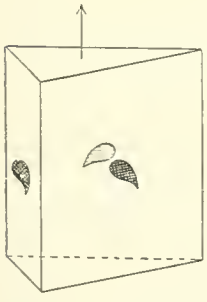

Fig. IX.
Trigonal Polar.

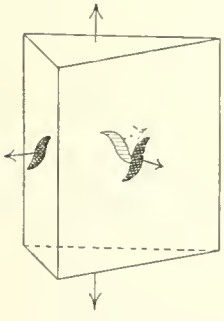

Fig. X.
Trigonal Holoaxial.

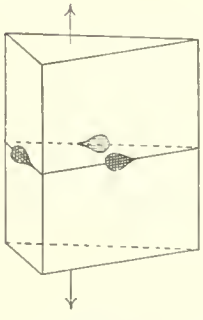

Fig. XI.
Trigonal Equatorial.

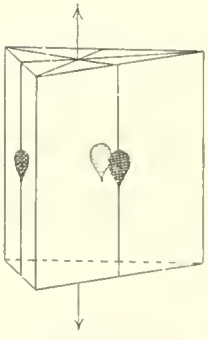

Fig. XII.
Ditrigonal Polar.

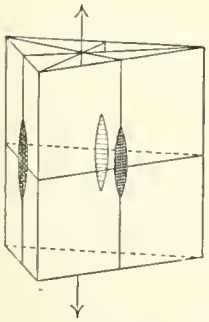

Fig. XIII.
Ditrigonal Equatoral.

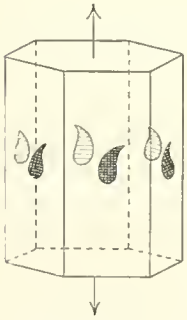

Fig. XIV.
Hexagonal Polar.

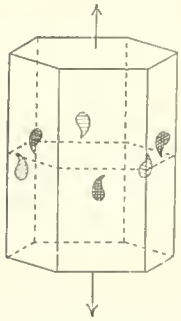

Fig. XV
Hexagonal Alternating.

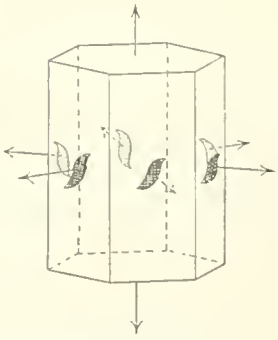

Fig. XVI.
Hexagonal Holoaxial.

THE 32 CLASSES EXHIBITED AS ETCHED PRISMS.

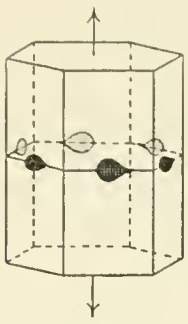

Fig. XVII.
Hexagonal Equatorial.

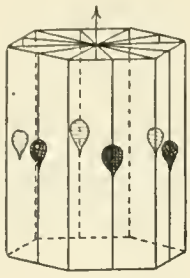

Fig. XVIII.
Dihexagonal Polar.

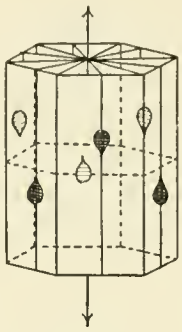

Fig. XIX.
Dihexagonal Alternating.

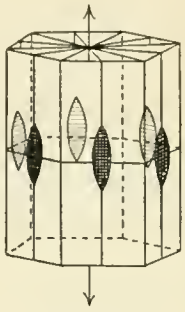

Fig. XX.
Dihexagonal Equatorial.

Fig. XXI.
Tetragonal Polar.

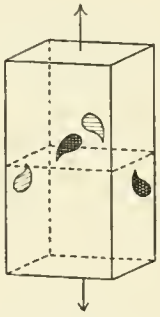

Fig. XXII.
Tetragonal Alternating.

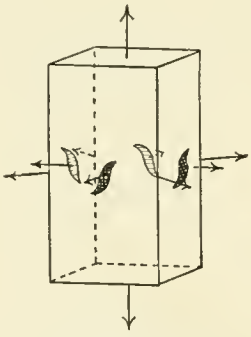

Fig. XXIII.
Tetragonal Holoaxial.

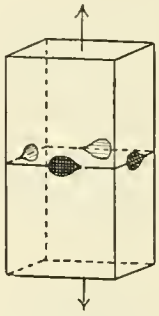

Fig. XXIV.
Tetragonal Equatorial.

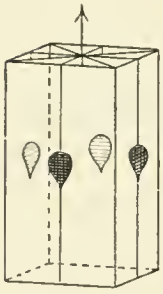

Fig. XXV.
Ditetragonal Polar.

Fig. XXVI.
Ditetragonal Alternating.

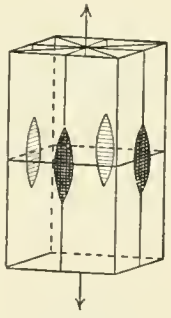

Fig. XXVII.
Ditetragonal Equatorial.

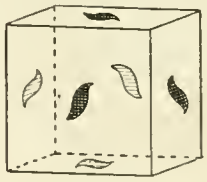

Fig. XXVIII.
Tesseral Polar.

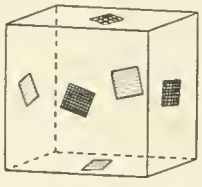

Fig. XXIX.
Tesseral Holoaxial.

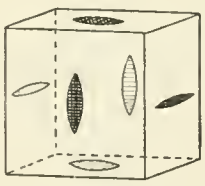

Fig. XXX.
Tesseral Central.

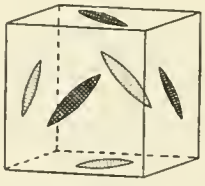

Fig. XXXI.
Ditesseral Polar.

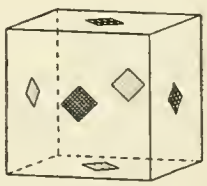

Fig. XXXII.
Ditesseral Central.

THE 32 CLASSES EXHIBITED AS ETCHED PRISMS.

APPENDIX II

THEORIES OF CRYSTAL STRUCTURE

THE earliest theory of crystal structure, that of Haüy, has been alluded to on p. 21 ; it is based upon the cleavage, and leads to the law of rational indices. We cannot, of course, believe that a crystal with cubic cleavage really consists of small cubes packed together, as in Fig. 37, so as to fill space without interstices ; but there are other ways of interpreting the structure. For example, let the cubes be replaced by spheres inscribed in them ; this would give a stack of equal spheres, each of which is in contact with its six neighbours, and the cubic structure is still that of Fig. 37.

Or, again, each cube may be replaced by a small particle placed at its centre, and the structure becomes a cubic assemblage of particles which are not in contact at all, but may be regarded as held together by their own forces of mutual attraction and repulsion (Fig. i.).

In such a structure the particles all lie along straight lines ; the line joining any pair of particles, if prolonged in both directions, will carry a series of particles at intervals equal to that which separates the two points chosen : moreover, the particles will be distributed in precisely the same way along a parallel line drawn through any other particle. Such a structure is therefore in complete harmony with the nature of a crystal as revealed by its physical properties, for all parallel directions are identical. Further, the particles are all distributed uniformly in planes ; the plane containing any three particles, if produced, will carry a series of particles uniformly distributed at the same intervals ; and these planes obey the law of rational indices. The structure is therefore in complete harmony with a crystal as regards its geometrical properties.

The structure of Fig. i. may be called that of the cube, since it is obtained by dividing space into cubic cells and placing a particle at the corner of each cell ; (it must be noticed that the same structure is obtained whether the particles be placed at the corners or at the centres of the cells).

Such a structure is called a **space-lattice** (*German*, Raumgitter ; *French*, Réseau) ; it is a net-like structure in which the particles are situated at the corners of parallel and equal parallelepipeda.

Now the simple cubic lattice is not the only one which satisfies the requirements of a crystal.

Between the years 1835 and 1856 Frankenheim and Bravais solved the problem—"How many kinds of space-lattice can be constructed?" and found the number to be fourteen. Each may be defined by the form of the cells into which it divides space.

The Fourteen Space-Lattices

i. The cube . . . . . Fig. i.
ii. The centred cube, *i.e.* the cube with a particle at each of its corners and one at its centre . . . . . Fig. ii.
iii. The cube with centred faces, *i.e.* the cube with a particle at each of its corners and one at the centre of each of its faces . . Fig. iii.
iv. The square prism (*cf.* Fig. 117) . . . . . Fig. iv.
v. The centred square prism . . . . . Fig. v.
vi. The prism of 120° (*cf.* Fig. xvi) . . . . . Fig. vi.
vii. The rhombohedron . . . . . Fig. vii.
viii. The orthorhombic prism (*cf.* Fig. 154) . . . . Fig. viii.
ix. The centred orthorhombic prism . . . . . Fig. ix.
x. The rectangular prism (*cf.* Fig. 138) . . . . . Fig. x.
xi. The centred rectangular prism . . . . . Fig. xi.
xii. The clinorhombic prism (*cf.* Fig. 205) . . . . Fig. xii.
xiii. The monoclinic parallelepiped (*cf.* Fig. 203) . . . . Fig. xiii.
xiv. The triclinic prism (*cf.* Fig. 213) . . . . . Fig. xiv.

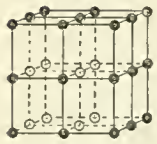

Fig. i.

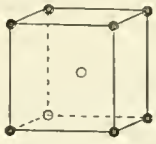

Fig. ii.

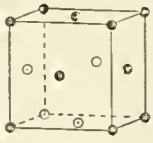

Fig. iii.

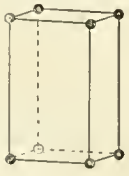

Fig. iv.

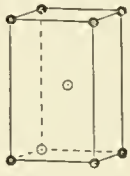

Fig. v.

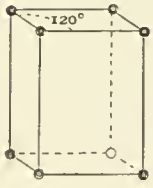

Fig. vi.

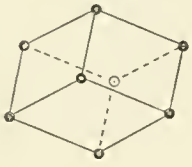

Fig. vii.

Fig. viii.

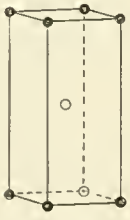

Fig ix.

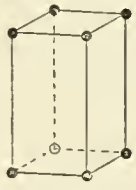

Fig. x.

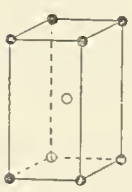

Fig xi.

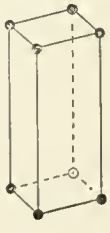

Fig xii.

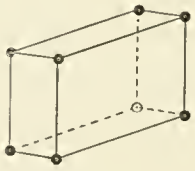

Fig. xiii.

Fig. xiv.

The fourteen space-lattices constructed from the above-described cells all possess the homogeneity and the anisotropic character (p. 106) of crystals, and the planes passing through any three of their points all obey the law of rational indices. But they possess a still more remarkable feature—each lattice has the symmetry of one of the systems of crystals, and all the six systems are represented among them as follows :—

i-iii.	Cubic System.
iv-v.	Tetragonal System.
vi-vii.	Hexagonal ,,
viii-xi.	Orthorhombic System.
xii-xiii.	Monoclinic ,,
xiv.	Anorthic ,,

It will be noticed, however, that only the symmetry of the holosymmetric classes is represented among the lattices ; if the remaining classes are to be accounted for, some additional supposition will have to be made. This may be done in two ways, either (1) by supposing the symmetry to depend not only upon the arrangement of the particles but also upon the symmetry of the particle itself, or (2) by considering new arrangements of particles which are not lattices.

1. Possible Differences in the Symmetry of the Constituent Particles.—In the lattices there is no distinction between opposite directions—for example, between a forward and a backward direction along any line of particles ; for this reason they cannot display the symmetry of any of the polar classes of crystals described above. But suppose that the particles themselves are pear-shaped, and are arranged along one of the lines with all their sharp ends pointing in one direction and their blunt ends in the other, then the structure may be expected to display a certain polarity in the direction of that line.

Thus, for example, let the particles in the cubic lattice of Fig. i. be all parallel tetrahedra whose edges are parallel to the diagonals of the cube faces ; then if account be taken, not only of the arrangement of the particles, but also of their own symmetry, the symmetry of the structure as a whole will be tetrahedral.

In some such way it will be possible to find representatives of all the thirty-two classes. Bravais attributed the various degrees of symmetry within one crystal system to the nature of the constituent particles.

2. Homogeneous Arrangements which are not Space-lattices.—Haüy himself pointed out that the cleavage does not always lead to figures with parallel faces like the fourteen cells considered above. Take, for example, a cleavage parallel to the faces of the hexagonal prism. Let Fig. xv. represent the base of the hexagonal prism ; cleavage

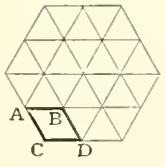

Fig. xv.

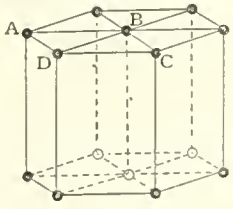

Fig. xvi.

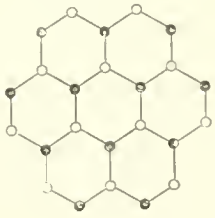

Fig. xvii.

parallel to its edges will divide it, not into hexagons, but into triangles, as shown in the figure. It is true that the triangles may be grouped together in pairs to form rhombs of 120° like A B C D ; but this is a purely arbitrary process, and if the cleavage is to represent the structure we must regard it as based upon, not the rhombic or hexagonal prism, but the triangular prism. Particles placed at the *corners* of these prisms, as in Fig. xvi., may equally well be regarded as placed at the corners of the rhombic prisms of 120° like A B C D, and the structure is the lattice of Fig. vi.

But the triangular prisms are in reality of two distinct sorts: half of them have the vertex pointing upwards in Fig. xv., and the other half point downwards. If, as in the case of the cubic structure, each prism be replaced by a particle situated at its centre, the arrangement is not a lattice at all, but the hexagonal or bee's-cell structure of Fig. xvii. Even if the particles of Fig. xvii. are all similar in nature, they are not similar in position, for one half ● are situated vertically above, and the other half ○ vertically below an adjacent particle. The structure consists in fact of two space-lattices ● and ○ thrust into one another in such a way that **about every point of the system the disposition of the remaining points is exactly the same** (although it may not always face the same way).

In this sense such a structure is homogeneous; it is the same throughout, and is thus in harmony with the physical requirements of a crystal.

To construct a system of points, like the bee's-cell arrangement, which fulfils this condition, it is necessary to choose one of the fourteen space-lattices described above; then to take one or more lattices identical with it and to thrust them into each other in such a way as to satisfy the above condition for homogeneity. The number of arrangements of this sort which can be constructed was investigated by Sohncke in 1879, and was found to be sixty-five, and among these so-called "regular point-systems" most of the thirty-two classes are represented.

But although the two or more space-lattices which make up the crystalline structure must be identical so far as the arrangement of their particles is concerned, one may conceivably consist of particles of one sort, and another of particles of a different sort. In fact, in some of the thirty-two classes we are driven to some such supposition.

Take, for example, the possible structure of the dioptase class with its hexagonal axis of alternating symmetry. This, like all such problems, may be treated by first uniformly partitioning space into cells, or filling it with solid figures, and then replacing each of these cells or figures by a particle.

Fig. xviii. represents a structure (of solid figures) which possesses an alternating hexagonal axis; it consists of rhombohedra, each of which is divided into six segments,

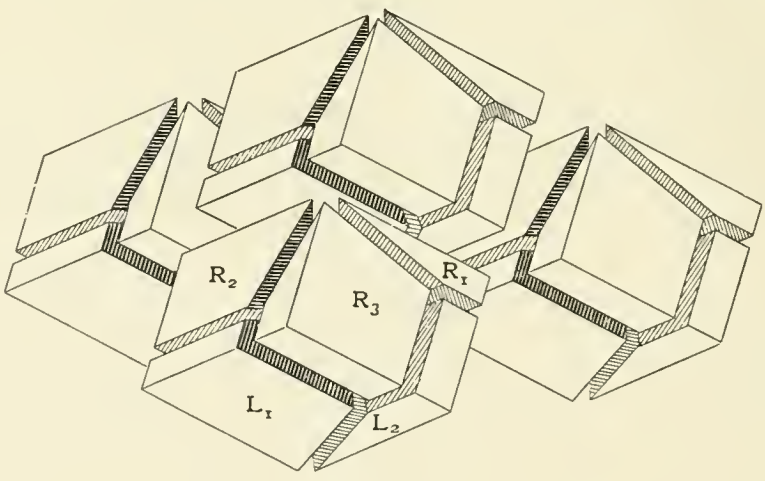

Fig. xviii.

but in each rhombohedron the three upper segments are in a certain sense quite different from the three lower segments, although they are figures of the same sort. An upper segment bears to a lower segment the same relation that a right hand bears to a left hand; they are enantiomorphous figures; one is the reflection of the other. Hence if each segment of Fig. xviii. be replaced by a particle in such a way as to preserve the symmetry of the structure, the particles must be of two sorts, and must

bear an enantiomorphous relation to each other.[1] Owing to this relation, each rhombohedron—and therefore also the whole structure—possesses centrosymmetry.

All the conceivable homogeneous arrangements to be obtained by combining space-lattices, either of the same sort or of opposite sorts of particles, have now been investigated, and it is found that although there are no less than 230 different arrangements, they all possess the symmetry of one or other of the thirty-two classes of crystals.

Finally, therefore, according to this theory a crystal may be regarded as a homogeneous assemblage of particles constructed of interpenetrant space-lattices, and it is the space-lattice which determines its system and its angles, and accounts for the law of rational indices.

One interesting property of a space-lattice may be mentioned. All parallel planes are identically constructed and are equidistant, but amongst all the differently inclined sets of planes in the lattice some are more thickly beset with particles than others. It can be proved that the planes which are most thickly beset with particles are most widely separated from the adjoining parallel planes.

If, as might be expected, the faces of common occurrence upon a crystal are those in which the particles are most dense, and the planes of cleavage are those which are least closely packed together, the coincidence of these two properties will explain the fact that cleavage generally takes place parallel to the faces of common forms. In any case both properties will combine to make the cleavage take place along certain faces alone.

If, as might also be expected, the particles of which isomorphous substances consist occupy nearly the same space and possess the same symmetry, they may form parts of the same structure, and so give rise to solid solutions. Again, if the structure be pseudosymmetric, so that one portion when turned round into a new position is only slightly changed, it may in like manner fit into or upon the other portion so as to constitute a continuous structure, and a mechanical explanation of the curious property of twinning is suggested.

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[1] Of course the structure may be regarded in another way; opposite particles may be coupled together in pairs, R with L, so as to form a segment possessing a centre of symmetry, and this figure may be regarded as the basis of the structure; but even so it consists essentially of a right and a left half which are enantiomorphous.

PART II

DESCRIPTION OF THE MORE IMPORTANT MINERAL SPECIES

SECTION I

THE ELEMENTS

DIAMOND, GRAPHITE

Diamond.[1]—Carbon, C. Cubic; symmetry, ditesseral polar. Common form, octahedron (supplementary twin of tetrahedra). Also twinned on (111). Cleavage {111}, perfect. Brittle. Fracture, conchoidal. H = 10; G = 3·52. Colourless. Lustre, adamantine. Transparent. Refraction very strong, $\mu = 2{\cdot}417$. Dispersion very strong = 0·063. Infusible. Insoluble in acids.

With the above description compare crystals from **Minas Geraes** (Brazil).

Diamond (*Germ.*, *Fr.*, Diamant), the hardest and most valuable of minerals, is naturally the one which excites the greatest popular

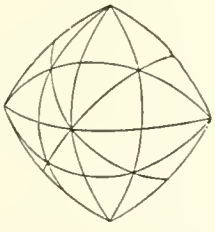

Fig. 419.—Diamond. Curved Octahedron.

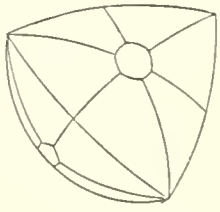

Fig. 420.—Diamond. Six-faced Tetrahedron.

interest; its value results mainly from the extraordinary hardness and the brilliance which together make it the most precious of gems; and these characteristics have been known from very early times. The modern scientific interest of the diamond has mainly centred round the vexed question of its origin in nature, and the attempts to reproduce it by artificial means; but, as will presently be shown, it has been the subject of much scientific investigation in other respects.

Diamond is practically unknown except as crystals, and is generally found (in river gravels, sands, and conglomerates) as isolated

[1] The short description at the head of each species gives the principal characters of typical specimens, and a locality by which they are illustrated is in each case cited; many of these characters (*e.g.* specific gravity, colour, optical properties) may differ considerably with varying chemical composition. The fusibility refers to the mouth blowpipe.

individuals. These usually appear to be simple octahedra, sometimes smooth and bright, but often curved and dull; other forms are known, such as the dodecahedron, and, more rarely, the cube. It used to be supposed that the Indian diamonds were mostly octahedral, and that the other two forms were characteristic of the Brazilian crystals; this is not really the case; among the South African diamonds many different forms have been found. A remarkable and characteristic feature is the curvature of the faces; owing to this peculiarity some of the small crystals appear almost like drops of gum. So far as is known from experiments, the curvature of crystal faces is generally due to the action of a solvent, and many diamond crystals present other features which may also be the result of corrosion; the cube is one of the rarest forms of diamond, but when present the cube faces are rough and drusy (Fig. 423); again the octahedron faces themselves, though sometimes smooth and brilliant, are often covered with the most beautifully regular triangular markings (shallow pits) which have the appearance of etched figures. These are the same upon all the eight faces of the octahedron, but they do not for that reason necessarily indicate that the crystal is holosymmetric. Many octahedra of diamond have a groove or furrow in the place of each octahedron edge (Fig. 421), and if these re-entrant angles indicate twinning, the crystals must in reality belong to the tetrahedrite class (ditesseral polar). Much controversy has taken place upon the question whether the diamond is really octahedral, as it appears, or tetrahedral, as is suggested by the grooves; the problem may now be regarded as decided in favour of the tetrahedrite class by the following two facts:—(1) Several crystals have been found which are undoubtedly simple crystals of tetrahedral habit; Fig. 420 represents a curved crystal which is simply the six-faced tetrahedron of Fig. 100 (p. 48); (2) the supplementary twinning of such crystals sufficiently explains all the other peculiarities of form.

Fig. 421.—Diamond. Supplementary Twin; Tetrahedra.

Fig. 422.—Diamond. Supplementary Twin.

In a supplementary twin of two tetrahedra, let the projecting corners be truncated by faces of the inverse tetrahedron as in Fig. 421. The twin crystal then presents the appearance of an octahedron with grooved edges, and it will be observed that the faces of this octahedron

all belong to the same sort of tetrahedron, and would all present the same corrosion figures if etched. Now let the interpenetrating crystals be, not tetrahedra, but the six-faced tetrahedron of Fig. 420, the resulting crystal is the octahedron with curved grooves of Fig. 422. This is a characteristic, if rare, form of diamond. Other curved and grooved crystals, such as the rounded cube of Fig. 423, can be explained as due to the same supplementary twinning.

The above growth, which may be geometrically described as due to reflection over a cube face (100), is not the only twinning known in diamond. "Spinel twins" of octahedra (p. 88) united along (111), as in Fig. 424, are by no means rare; they are known to the

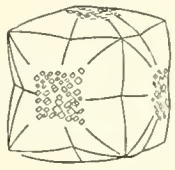

Fig. 423.—Diamond. Supplementary Twin; Cube.

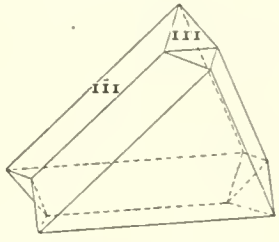

Fig. 424.—Diamond. Spinel Twin.

Amsterdam jewellers by the name of "Naht-steine," in allusion to the suture line or twin junction of the two crystals. These twins, as is the case with the twin crystals of many other substances, are flattened along the composition plane.

Only in the latter twins is the perfect octahedral cleavage interrupted by a re-entrant angle; the supplementary twins (of Fig. 422) cleave like single individuals, since the {111} faces are parallel throughout.

This perfect cleavage is of great use to the diamond cutters, since it enables them to chip away projecting corners and inferior parts of the stones, without incurring the labour of grinding them away: the labour of grinding facets upon a diamond is very great on account of its extreme hardness. The diamond is, in fact, the hardest substance known, and can be easily distinguished from all other minerals by this property; it is for this reason one of the most potent cutting, grinding, and polishing agents, and can be itself polished only by diamond powder; it is used as the cutting point in the determination of the hardness of other minerals by means of the sclerometer (p. 110). Metal discs charged with diamond dust are generally used for cutting thin sections of rocks and other hard substances for the microscope, and the same material is used in the working and polishing of most hard ornamental stones. Diamond is also used for the cutting points in drills for rock-boring purposes. In turning the axes of transit instruments, diamond has been employed as the hardest turning tool available. The cutting edge used by glass-cutters is usually the acute angle between a natural curved face and a cleavage plane; its efficiency is said to be due to the curvature, which prevents more than one point

of the cutting edge from being in contact with the glass. As is probably the case in any crystal, the hardness is different on the faces of different forms, being greater upon the cube than upon the octahedron face. Different specimens of diamond also differ somewhat in hardness, and the Australian and Borneo stones are reputed to be the hardest.

The hardness and consequent durability of the diamond confer upon this mineral much of its value as a gem stone. Other minerals (titanite for example) possess optical properties which would render them valuable as gems, were they not too soft, whereas diamond is practically indestructible by friction; it is, further, unaffected by acids.

The indestructibility of the diamond was well known to the ancients, and accounts for the Greek name ἀδάμας (the invincible), of which the modern names adamant, diamant, diamond, are corruptions. It is certain that the ἀδάμας of Greek authors does not always refer to the diamond; but in the *Historia Naturalis* of Pliny, at any rate, there is a detailed description of the stone which mentions its hardness, resistance to fire, and occurrence with gold, and leaves no doubt in the identification. Pliny distinguishes six different varieties. Of the Indian diamond he says that it resembles rock crystal by its transparence, and by its pointed hexagonal termination (*laterum sexangula laevore turbinatus in mucronem*); sometimes, he adds, it appears to be formed by two halves resembling two cones united by their base. In this description we may perhaps recognise one of the twinned forms.

By Pliny and by many ancient and mediæval writers the hardness was confused with toughness, and it was stated that the diamond resists all attempts to break it, so that if laid upon an anvil and struck with a hammer both anvil and hammer will fly to pieces before the diamond is broken. According to Bauer, the diamond hunters have been under the same delusion, and have broken many fine stones in applying this as a test. The tales about the indestructibility of the diamond are, however, rejected by Böetius de Boot in his book on stones published in 1609.

The diamond was also believed to be incombustible, until an experiment made by the Florentine Academicians in 1694 proved that it could be burnt, either in the furnace or by the concentration of the sun's rays. Newton had previously asserted that the high refractive power of the diamond indicates that it must be a combustible substance.

Subsequent experiments, especially those of Davy (1816) and Krause (1890), have proved not only that diamond can be burnt, but that the only product of combustion is carbon dioxide, and therefore that diamond is pure carbon.

A fragment of diamond can, with some difficulty, be consumed by heating on platinum foil before the blowpipe—but it requires to be raised to a temperature of about 900° C., and to be maintained at that temperature.

Although the diamond is usually colourless, yellow crystals are common, especially from South Africa; blue, green, and red are rare colours, and consequently add much to the value of the stone.

When coloured diamonds are heated they do not lose their colour, although it is sometimes altered; this indicates that the colour is not due to hydrocarbons, as has been supposed, but probably to metallic oxides.

The lustre is often more greasy than adamantine. Like all substances of adamantine lustre, the diamond possesses a very high refractive index (2·417), which is quite enough to distinguish it from all artificial imitations made of glass, since their index is not above 1·8. Other minerals which have a higher refractive power than the diamond, such as cuprite (2·85), cinnabar (3·02), proustite (2·94), crocoite (2·42), anatase (2·55), rutile (2·76), are coloured and far less transparent. Owing to this high index any rays which meet the internal surface of a diamond at angles greater than $24\frac{1}{2}^\circ$ are totally reflected, so that most of the light which enters a well-facetted stone emerges again after internal reflections, and this gives the gem its extraordinary lustre. This result is admirably attained by the "brilliant" mode of facetting which is reputed to have been the discovery of Cardinal Mazarin. The dispersion (0·063) is greater than that of all other precious stones except titanite. To this are due the brilliant colours ("fire") of the light refracted from a facetted diamond.

Many diamonds are perfectly isotropic, but some exhibit a double refraction, which was attributed by Brewster to internal strain, since it is most noticeable in the neighbourhood of cavities; he supposed this to prove that the diamond had once been sufficiently soft to be compressible by the gases confined in these cavities; but the birefringence is often so regular, being indicated by a network of bands inclined at the octahedron angle, or by a patchwork of triangular fields, that it is evidently connected with the crystalline structure.

This may indicate that the diamond is really pseudo-cubic, as was supposed by Mallard; or the birefringence may be due to strain, and may either be the result of external pressure when the diamond was formed, or of contraction on cooling, or of the interpenetration twinning.

A remarkable optical property of the diamond is its phosphorescence; most specimens can be easily made to emit light by friction upon wood, and they phosphoresce most beautifully when submitted to the electric discharge in a vacuum tube. It has been observed that the light emitted by the cube faces is different from that emitted by the octahedron faces.

Two other remarkable modifications of carbon are generally regarded as varieties of diamond. *Boart* is a semi-crystalline translucent substance, generally rather dark in colour, and with a curved drusy surface; sometimes a single stone consists of diamond in one part and of boart in another. The true boart of Brazil has a radial fibrous structure, and is much prized for use in rock drills. The name boart, however, is often used to denote those inferior crystals and fragments of diamond which are not fit for gem stones.

Carbonado is a still harder and more compact substance; it is a dull black opaque material, somewhat porous, so that it resembles charcoal

in appearance, and is absolutely devoid of cleavage; it is actually somewhat harder than the diamond itself; owing to these qualities it is of the greatest value for rock drills.

Carbonado is only found in the diamond deposits of Bahia (Brazil), in angular fragments which sometimes display a rude crystalline (cubic) form.

In India, Brazil, Borneo, and other parts of the world, diamonds are to be found in river sands and gravels, where they may have survived the friction of ages owing to their superior hardness, but their occurrence in such secondary deposits throws no light upon the real origin of the mineral. In South Africa, however, where they were also originally found in gravels of the Vaal river (the "river diggings"), they were subsequently discovered in far greater quantities in the peculiar deposits known as the "dry diggings" described below.

Most of the largest and finest diamonds have been found, as might be expected, in river washings and gravels where they have been sifted by the mechanical action of water from lighter and smaller stones. Among the most famous diamonds may be mentioned the Koh-i-Nur, which weighed 186 carats [1] (about $1\frac{1}{4}$ ozs.) when brought from India, and now, after re-cutting, 106 carats; the Orloff, weighing (cut) 93 carats, which is now one of the Russian Crown jewels; the Regent or Pitt, weighing (cut) 137 carats, one of the French Crown jewels; the Star of the South, a Brazilian stone which weighed 254 carats when found; the *green* Dresden diamond, preserved in the Green Vaults of the Saxon royal family; the *blue* Hope Diamond, which was stolen with other French Crown jewels in 1792; the Stewart, a South African stone which weighed 288 carats when found; and the Porter Rhodes, a white South African stone which weighed no less than 457 carats (about 3 ozs.).

A Noteworthy Locality:

Kimberley (South Africa).—In the "dry diggings" diamond occurs as etched octahedra with curved edges (Fig. 419) and somewhat greasy lustre enclosed in a greenish serpentinous breccia containing grains of red garnet, grains of various green pyroxenes, glittering scales of an altered magnesia mica (known as vaalite), and black granules of ilmenite. The dry diggings are vertical pipes of unknown depth, and 200 yards or more in diameter at the surface; the diamonds are disseminated through the brecciated serpentinous material with which these pipes are filled; this material is known as "blue ground" and contains fragments of many minerals and rocks. Different opinions have been held concerning the origin of these vast pipes and of the diamonds which are found in them; it has generally been maintained that the pipes themselves are volcanic and that the blue ground is an altered peridotite (olivine rock) from which the diamond has crystallised; and the alteration of the peridotite has been ascribed to hydrothermal action; the original source of the carbon has

[1] 1 (London) carat = 3·17 grains = ·2055 gram; 1 oz. = 151·4 carats.

by many writers been sought in the carbonaceous shales which have been cut through and dissolved by the blue ground. That the latter is a possible solvent of the diamond has been proved by actually heating diamond in the blue ground, when it becomes corroded, etched, and finally dissolved. Quite recently blocks of an eclogite containing small diamonds have been found in the dry diggings; eclogite must consequently be regarded as a parent rock of the mineral in the Kimberley district.

Graphite.—Carbon, C. Pseudo-hexagonal? Common form, hexagonal plates. Cleavage, basal, perfect. Pliable. H = 1; G = 2. Iron-black. Streak, gray. Lustre, metallic. Opaque. Infusible. Insoluble in acids.

With the above description compare crystals from **Pargas** (Finland).

Graphite, the other modification of carbon, presents a most marked contrast to diamond; it is one of the softest, as diamond is one of the hardest, of minerals; it is a good conductor of electricity, whereas diamond is a non-conductor; it rarely occurs in crystals, and these are only imperfect hexagonal plates with triangular striations. The crystals from Finland mentioned above occur in a crystalline limestone. Unsuccessful attempts have been made to determine the system of graphite from the percussion figures and from the figures produced by etching with chlorine gas, but these are not sufficient to distinguish between hexagonal and monoclinic symmetry; in the case of many other dimorphous substances of which one modification is cubic, the second is hexagonal, and it is argued that for this reason the presumption is in favour of hexagonal symmetry for graphite. Crystals of graphite have for the most part been found in crystalline schists, gneisses, and limestones. In thin laminæ graphite is pliable; it is greasy to the touch.

The softness of graphite causes it to leave a mark when rubbed on paper, and makes it suitable for pencils, and for polishing grates or for use as a dry lubricant; the name is derived from γράφω, I write. The so-called "black-lead" of Borrowdale in Cumberland has been worked since the sixteenth century; it is a compact graphite which occurs in large quantities associated with basic igneous rocks.

The specific heat of diamond (0·12) at ordinary temperatures is less than that of graphite (0·18), but in both minerals it becomes nearly equal (about 0·5) at high temperatures.

Diamond is not converted into graphite by ordinary combustion, but it is transformed into a mass of graphite scales when heated in the electric arc; it is also blackened when subjected to electric bombardment in a vacuum tube, and this is probably due to a superficial alteration into graphite.

Many attempts have been made to effect the reverse change and convert other forms of carbon into diamond, mostly without success. Graphite itself is often obtained as an artificial product; for example, in iron works, as crystalline scales separated by the blast from molten iron which

contains carbon, or as segregations in the preparation of carborundum. The artificial production of diamond, however, can scarcely be said to have been achieved until the recent experiments of Moissan. It has long been known that graphitic nodules are by no means rare in meteoric iron; from some meteorites have been extracted *cubic crystals* of graphitic carbon (cliftonite), some of which may be altered diamond; and some meteorites, conspicuously one mass of iron found at Cañon Diablo in Arizona, have yielded actual diamond crystals of appreciable size. In Moissan's experiments, also, iron was used as the solvent. Soft iron enclosing pure carbon was fused in the electric furnace and cooled by immersion in water; in this way the carbon within the iron dissolved at a high temperature, was made to separate from the solvent under a great pressure produced by the cooled and contracted crust of solid iron, and made its appearance as crystallised diamond.

A Noteworthy Locality:

Ceylon.—Vast quantities of graphite are mined in Ceylon, where it fills true veins in the granulite and associated rocks; the graphite sometimes has a columnar structure transverse to the vein, but where the rocks have been disturbed the soft graphite has been crushed and contorted, and is sometimes reduced to a scaly mass like the nodules segregated in carborundum.

SULPHUR

Sulphur.—S. Orthorhombic; symmetry, holoaxial.

$$a : b : c = 0{\cdot}813 : 1 : 1{\cdot}903.$$

$$\mathrm{P} = \{111\},\ p = \{11\bar{1}\},\ \mathrm{S} = \{113\},\ n = \{011\},\ \mathrm{C} = \{001\},\ e = \{101\}.$$

$$\mathrm{P}p\ (111) : (1\bar{1}1) = 73^\circ\ 34',\ \mathrm{PC}\ (111) : (001) = 71^\circ\ 39',$$
$$e\mathrm{C}\ (101) : (001) = 66^\circ\ 52'.$$

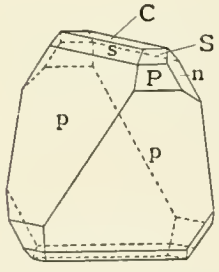

Fig. 425.—Sulphur. Tetrahedral Habit; P {111}, S {113}, p {$11\bar{1}$}, s {$1\bar{1}3$}, n {011}, C {001}.

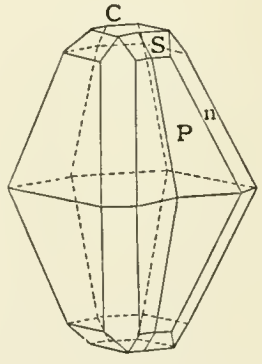

Fig. 426.—Sulphur, twinned on ($1\bar{1}0$).

Common form, bipyramid.. Cleavage {001}, {110}, very imperfect. Brittle. Fracture, conchoidal. H = 2; G = 2. Sulphur-yellow. Streak, white. Lustre, resinous-adamantine. Transparent. Refraction strong; $\beta = 2{\cdot}04$. Birefringence

very strong, positive; $\gamma - \alpha = 0{\cdot}290$. Axial plane (010). Acute bisectrix perp. to C. $2H = 104°$. $\rho < v$. Easily fusible, at 108°. Volatilises and burns. Insoluble in acids.

With the above description compare crystals from **Girgenti** (Sicily).

Sulphur (*Germ.* Schwefel, *Fr.* Soufre, *Span.* Azufre) is found in large and beautiful crystals at Girgenti in Sicily. These are generally the rhombic bipyramids of Fig. 427; but on some specimens the crystals are markedly sphenoidal (*i.e.* tetrahedral) in habit, and it is therefore nearly certain that the mineral belongs in reality to the holoaxial class. Fig. 425 represents such a crystal; and even in Fig. 427 P is slightly larger than *p*, but it has not been possible to find any certain external difference between the faces P $\{111\}$ and *p* $\{\bar{1}\bar{1}1\}$. Twinning, though rare, is known according to no less than four different laws: namely by reflection over (101), (011), (110) and (111). Fig. 426 represents a crystal from the Solfatara of Cattolica in Sicily, twinned thus by juxtaposition on $(1\bar{1}0)$: the other twins are generally more or less interpenetrant, sometimes even cruciform. In addition to its strong refraction and birefringence, sulphur possesses another remarkable optical peculiarity; the angle between the primary optic axes is 72° 20′, and that between the secondary optic axes is 64° 57′; so that the angle between a primary and a secondary optic axis, which in most minerals is only a few minutes, is in sulphur 3° 42′.

The heat-conductivity of sulphur is so low that the warmth of the fingers is sufficient to cause a crystal to crack if it be incautiously handled; and if it be held in the hand close to the ear a crackling sound may be heard from the same cause.

The best and largest crystals of sulphur are not those which have been formed by sublimation from sulphur vapours in volcanic regions, but are found (as in Sicily) in marl or clay associated with such minerals as calcite, aragonite, gypsum, and celestite, where they appear to have been deposited from hot waters. The sublimation deposits usually occur as incrustations. In metallic veins sulphur may occur as a result of the decomposition of sulphides. Owing to the variety of its modes of origin, sulphur is found in many forms; very commonly as reniform, irregular, or earthy masses; while the colour, especially of the earthy varieties, may be orange, brown, or gray.

Sulphur is polymorphous; when fused and allowed to crystallise from the molten state it assumes an entirely different form belonging to the monoclinic system; this modification has rarely (perhaps never) been found as a mineral; it readily passes into the orthorhombic modification, which is the more stable at ordinary temperatures; in fact the artificial monoclinic crystals generally become dull and brittle after a time, through their spontaneous conversion into minute orthorhombic bipyramids. The orthorhombic crystals may be obtained artificially by allowing sulphur to crystallise from solution in carbon disulphide.

In addition to these two, no less than three other modifications of sulphur have been obtained, one of which may be isomorphous with one of the modifications of tellurium.

Sulphur is distinguished from all other minerals by easily burning with the production of acid vapours (SO_2) of pungent odour.

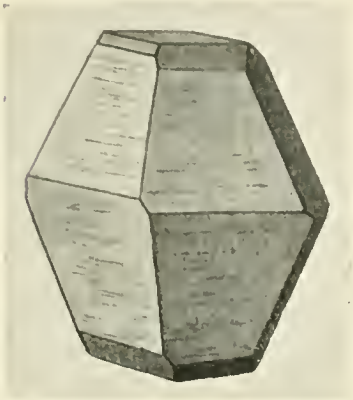

Fig. 427.—Sulphur.
Usual Habit.

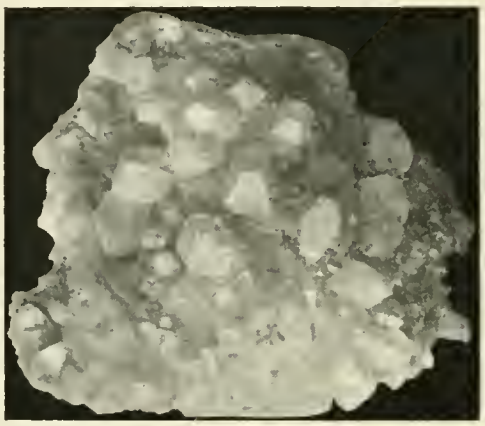

Fig. 428.—Sulphur from Girgenti
(British Museum).

A Noteworthy Locality:

Girgenti (Sicily), Fig. 428.—Beautiful crystals, usually bipyramids {111} with {113} and {001}; more rarely of tetrahedral habit, accompanied by crystals or crystalline crusts of white celestite; the latter is either in prisms or in acute pyramids. The best specimens are from Roccalmuto and Cattolica; the sulphur is not a sublimation product of volcanic origin, but occurs in beds of a calcareous marl in the nummulitic limestone.

THE ARSENIC GROUP

Arsenic.—As. Hexagonal; symmetry, dihexagonal-alternating (calcite class). $100 : 010 = 94° 54'$. Cleavage {111}, perfect; {110}, imperfect. Brittle, slightly sectile. Fracture, uneven. $H = 3\frac{1}{2}$; $G = 5{\cdot}7$. Silver-white. Streak, black. Lustre, metallic. Opaque. Volatilises without fusion. Oxidised by nitric acid.

With the above description compare crystalline material from **Schneeberg** (Saxony).

Antimony.—Sb. Hexagonal; symmetry, dihexagonal-alternating (calcite class). $100 : 010 = 92° 53'$. Cleavage {111}, perfect; {110}, fair; $\{11\bar{1}\}$, imperfect. Brittle. Fracture, uneven. $H = 3\frac{1}{2}$; $G = 6{\cdot}6$. Tin-white. Streak, tin-white. Lustre, metallic. Opaque. Easily fusible. Volatilises. Oxidised by nitric acid.

With the above description compare crystalline material from **Andreasberg** (Harz).

Bismuth.—Bi. Hexagonal; symmetry, dihexagonal-alternating (calcite class). $100 : 010 = 92° 20'$. Cleavage {111}, perfect; $\{11\bar{1}\}$, fair. Sectile.

Fracture, crystalline. H = 2½; G = 9·8. Silver-white (reddish). Streak, gray. Lustre, metallic. Opaque. Easily fusible. Volatilises. Soluble in nitric acid.

With the above description compare crystalline material from **Schneeberg** (Saxony).

Arsenic, antimony, and **bismuth,** three minerals which generally occur only as crystalline granular masses or botryoidal and curvilaminar crusts, constitute an isomorphous group of rhombohedral elements which are allied to the non-metal sulphur in some of their properties, and to the metals proper in others. They may be regarded as a transitional group (isomorphous with tellurium and zinc) leading to the metals. They may be recognised by their metallic appearance, and platy structure, and by the brilliant basal cleavage.

The secondary, rhombohedral cleavages given above may be due to separation along planes of twinning. Native arsenic and antimony are of considerable commercial importance as sources of these metals. Native antimony generally contains arsenic, while native bismuth contains both arsenic and antimony. Beautifully tarnished crystals of bismuth, resembling skeletal cubes (the angle of {100} in this group is very nearly a right angle) are formed from fusion during the manufacture of this metal.

THE GOLD GROUP

Gold.—Au. Cubic, holosymmetric. Common form, elongated octahedron. Malleable; ductile. Fracture, hackly. H = 2½; G = 19·3. Colour, gold-yellow. Lustre, metallic. Opaque. Fusible (at 1200°). Insoluble in acids, except *aqua regia*.

With the above description compare crystallised groups from **California**.

Fig. 429.—Gold. Reticulated Plate from Colombia (British Museum).

Gold (*Fr.* Or, *Ital.* Oro), like diamond, has always been one of the most familiar minerals on account of its value; and the value of gold, like that of diamond, is due not only to the rarity, but also to the durability of the metal; it further resembles diamond in the fact that its chief scientific interest to the mineralogist results from the mystery that surrounds the origin of this metal. On the other hand, whereas attempts to reproduce diamond are only modern, and have been crowned with success, the attempts to reproduce gold have been abandoned since the failures of the alchemists of the Middle Ages, to

whom it was a fascinating problem. Again, unlike diamond, gold is durable not by virtue of hardness but only because it resists the action of solvents. For this reason gold ornaments belonging to the very earliest periods have been preserved. Cloisonné work found in Egypt dates from the twelfth dynasty (2500 B.C. ?), and the flint implements with gilt handles found in the same country must be much earlier.

Although the largest masses of gold have been found as nuggets in the gravels and sands which have been so fruitful a source of the precious minerals, it is very seldom under these conditions found crystallised. Well-defined crystals are altogether rare, but they are sometimes found in metalliferous veins, or where the gold occurs in quartz "reefs," as in Hungary, Russia, Australia, Brazil, and California. The form of crystals from Transylvania in particular has been carefully studied; among them are sharply-defined cubes and cubo-octahedra, but they are very often rod-shaped and elongated along the edge in which cube and octahedron faces intersect, or they are platy and flattened along an octahedron face. Such rods and plates, being united by twinning on (111), give rise to remarkable dendritic groups and tesselated surfaces.

Fig. 430 represents the twinning by which vom Rath explained the structure of a reticulated gold group from Hungary. Each rib is apparently a rhombic prism of 70° 32′, but is really a combination of two elongated cubes, terminated by faces of $e\{210\}$, extended in the direction of one of the diagonals of a cube face; a pair of these are twinned together, united along the octahedron face and interpenetrating; the cube faces A are striated parallel to their intersections with e; several ribs are further united to each other by twinning about other faces of the octahedron, and by elongation along other diagonals of the cube faces.

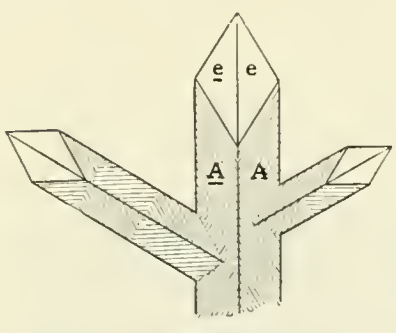

Fig. 430.—Gold. Twin Group; A {100}, e {210}.

Twinning upon the octahedron, and the misshapen aspect due to elongation of the crystals along a ditrigonal axis, or to flattening along the octahedron face, suffice to explain all the most fantastic and complicated forms of gold; some of these present the appearance of hexagonal pyramids or monoclinic plates, and have even been described as such, but there is no reason to believe that gold is anything but cubic and holosymmetric. Faces of $\{hk0\}$ and $\{hkk\}$ can often be distinguished in addition to cube, octahedron, and dodecahedron, but the crystals are usually rounded, curved, or uneven, and consequently difficult to decipher. The rounding of the edges is not due to fusion, although gold sometimes presents quite the appearance of fused crystals.

The metal is fusible at about 1200°, and (like silver) melts to such perfectly spherical globules that a microscopical measurement of the dimensions of the button obtained in an assay may be employed as a measure of the amount of gold contained in the sample.

All gold contains more or less silver, and those specimens which

contain most silver are palest in colour, and are also the hardest and the least dense; with only 10 per cent of silver the specific gravity is as low as 17·7. The purest natural gold is said to be that of Mount Morgan in Queensland (99·7 per cent Au). Most of the Hungarian gold contains about 30 per cent of silver. Since the time of Pliny such argentiferous varieties of gold have been called "electrum" (*ubicunque quinta argenti portio est, electrum vocatur*). The name electrum originally signified amber and was no doubt applied to gold on account of its colour. The crystals of Hungarian electrum are among the sharpest and best, and this variety must be regarded as a solid solution of the isomorphous metals gold and silver.

It is only necessary here to allude briefly to the various modes of occurrence of gold and the theories relating to its origin, so far as they are connected with the properties of the metal.

In addition to the nuggets, grains, and scales of gold found in sands and gravels of secondary origin ("placer deposits"), which have clearly not been formed at the spot where they are now found, there are four well-defined types of gold deposits:—(1) Metalliferous veins, which contain gold enclosed in, or accompanying, metallic sulphides, especially iron pyrites; (2) quartz reefs, which are veins or masses of quartz containing gold in the metallic state disseminated through the quartz; auriferous sulphides also accompany the quartz reefs; it is from such deposits that many of the crystallised specimens to be seen in museums are derived; (3) the "banket" formation of the South African Gold Fields, which is a quartzite conglomerate rich in gold so finely disseminated as to be for the most part invisible; (4) the siliceous sinter of Mount Morgan in Queensland, a ferruginous sinter which is richly impregnated with the metal.

In the three last types of deposit the gold is generally supposed to have been introduced by percolating solutions simultaneously with the silica, and to have been derived from the decomposition of metallic sulphides in which it was originally contained. The outcrop of auriferous lodes generally consists of a cellular ferruginous quartz known as "gossan" (the *eiserner Hut* of the Germans, Fr. *chapeau de fer*), which is filled with hydrates and silicates of iron, the decomposition products of iron ores. In the Mount Morgan deposits the agency appears to have been clearly that of heated water; and it is said that gold is being deposited at the present day by the hot water of the Steamboat Springs in Nevada.

On the other hand, no natural compounds of gold are known except tellurides, and it is not understood in what way the metal can have been carried in solution, whether as chloride, as has been suggested by some, or as an alkaline aurate, as has been held by others.

The origin of the nuggets found in placer deposits has been the subject of equal controversy, for it has been asserted that they are both larger and purer than any masses of gold found in reefs similar to those from which they might have been derived; consequently it has been supposed that they have not been washed out from the debris of

reefs but have grown by accretion in these deposits through the agency of some percolating solution. It has, however, been shown that a gold nugget polished and etched with acids displays a crystalline structure throughout like that of Fig. 4, p. 4, and never a curvilaminar, or onion-like, structure, such as would result from successive layers deposited round a nucleus.

The gold contained in auriferous pyrites is not present as any compound in isomorphous mixture, but as a metal disseminated through the crystal. Sometimes in the pyrites and in the prisms of aikinite at Beresov, in the Urals, there is a nucleus or rod of gold which seems to indicate that the metal has become concentrated mechanically within the crystal, and it is possible that some such mechanical concentration has taken place elsewhere and under other conditions.

In connection with the origin of gold it may be borne in mind that all sea water and many fresh waters contain gold in appreciable quantities; this element is, in fact, one of the most widely distributed of minerals.

A Noteworthy Locality:

Verespatak (Transylvania).—Veins which traverse the conglomerates, trachytes, andesites, and dacites of this region have been worked for gold since Roman times. The gold, both crystallised and in mossy, leafy, and wiry forms, accompanies amethyst and quartz, blende, calcite, rhodochrosite, iron pyrites, and other minerals; it is generally of pale colour, and much twinned.

To the series of native "heavy metals," which are mostly malleable (or flatten under the knife), and which crystallise in the cubic system, belong not only gold, copper, silver, and platinum, but also the metals **mercury**, **lead**, **iron**, **palladium**, **and iridium**, these last five only occurring very rarely.

Of these gold, silver, copper, mercury, and lead are isomorphous and constitute the gold group.

Silver.—Ag. Cubic, holosymmetric. Common form, cubes. Twinned on (111). Malleable; ductile. Fracture, hackly. H = $2\frac{1}{2}$; G = 10·5. Silver-white. Lustre, metallic. Opaque. Fusible (at 1050°). Soluble in nitric acid.

With the above description compare crystallised groups from **Kongsberg** (Norway).

Copper.—Cu. Cubic, holosymmetric. Common form, elongated four-faced cubes $\{hk0\}$. Twinned on (111). Malleable; ductile. Fracture, hackly. H = $2\frac{1}{2}$. G = 8·9. Copper-red. Lustre, metallic. Opaque. Fusible at 780°. Soluble in nitric acid.

With the above description compare crystallised groups from **Lake Superior.**

Platinum. — Pt. System, cubic, holosymmetric. Malleable; ductile. Fracture, hackly. H = $4\frac{1}{2}$; G = 19. Light steel-gray. Lustre, metallic. Opaque. Infusible. Insoluble in acids except *aqua regia.*

With the above description compare crystallised grains from **Nizhni Tagil** (Perm, Russia).

The metals of this series are seldom pure, and isomorphous mixtures (or alloys) are common; gold, as we have seen, always contains silver, the quantity varying from 0·3 to 10 or more per cent; silver contains both gold and copper; copper contains silver. Platinum contains iron, iridium, and palladium.

Mercury is only found in liquid globules, but is known to belong to this group, for native amalgam, an alloy of silver and mercury, is found at Moschel (Rhenish Bavaria), in bright silver-white crystals ({100} {110} {111}) belonging to the cubic system; moreover, mercury itself can be crystallised in octahedra by cooling it down to −40° C.

Gold is perhaps dimorphous, for an alloy of gold and tin having a composition near $AuSn_3$ belongs to the tetragonal system, and is apparently isomorphous with tin.

Crystals of all the minerals belonging to this group are rare; platinum, like gold, is mostly found in rolled nuggets, while crystals of

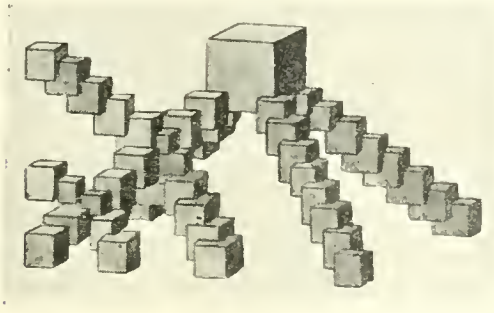

Fig. 431.—Silver. Skeletal Growth.

Fig. 432.—Copper from Lake Superior; Twin Group.

silver and copper resemble crystallised gold in being generally curved, uneven, or skeletal with rounded edges. Very fair cubes and cubo-octahedra of silver have been found at Kongsberg in Norway; the skeletal crystals of this metal are due to elongation or to parallel grouping in the direction of the cube-diagonals, as shown diagrammatically in Fig. 431. Similarly, copper is found in large and distinct cubes, octahedra, and dodecahedra in the Lake Superior mining region; and the prevalence of faces $\{hk0\}$ in combination with these forms together with frequent elongation along the ditrigonal axis gives the crystals the aspect of complicated hexagonal forms. Fig. 432 (after Dana) represents cubes from Lake Superior elongated along the twin plane (which is perpendicular to the paper), so that the crystal resembles a rhombic pyramid. These distortions, and also the twinning on (111), are as common with silver and copper as with gold, and much that was said above about the latter will apply equally to them. Owing to these causes they frequently occur in dendritic and arborescent groups, of which the fronds are sometimes due to parallel growth of crystals so elongated that the rays meet at angles of 60°, but more usually to twinning on faces of the octahedron (*cf.* Fig. 398, p. 250).

Silver is often found in remarkable filiform and stringy masses (Fig. 433), gold in thin sheets, scales, and flakes, or even as dust.

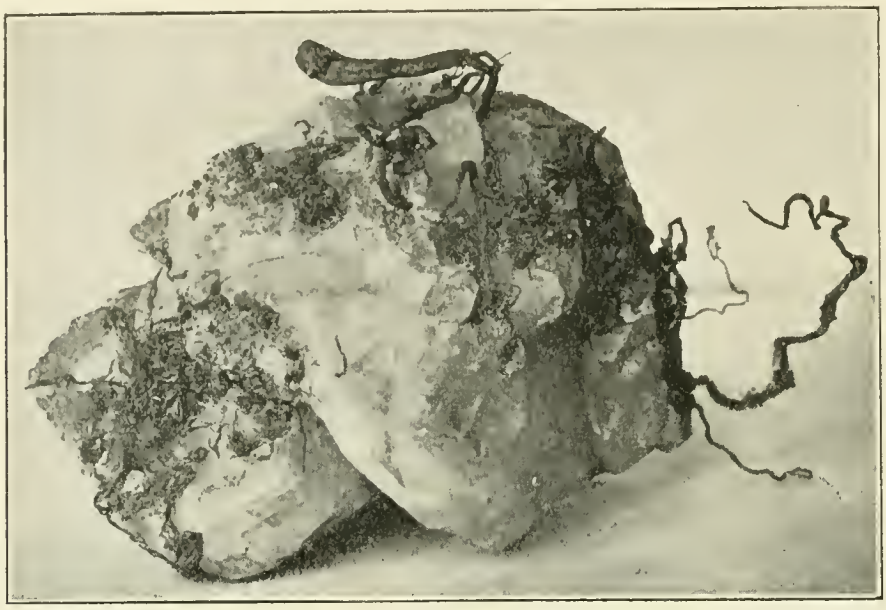

Fig. 433.—Wiry Silver from Norway (British Museum).

Their malleability, colour, and weight are sufficient to distinguish this group:—gold from iron pyrites or chalcopyrite, and gold dust from mica scales; silver from argentite and other sectile sulphides; copper from all other minerals.

Platinum and gold are not liable to tarnish; silver is usually more or less blackened by surface alteration and sometimes converted into the black sulphide of silver (argentite); copper is generally brown or black on a tarnished surface, and is very liable to alteration, passing into the blue carbonate (chessylite), the green carbonate (malachite), or the red oxide (cuprite), by all of which it is often encrusted.

Several of these metals have been found in very large masses; the "Welcome" gold nugget found at Ballarat in Australia weighed 184 lbs.; a mass of silver from Kongsberg in Norway, now preserved at Copenhagen, weighs 500 lbs.; and a mass of copper found in the Lake Superior mines was 45 feet in length and weighed 420 tons. Iron has also been found in large masses weighing as much as 20 tons at Disco Island in West Greenland; the Cranbourne meteoric iron (from Australia) in the British Museum weighs $3\frac{1}{2}$ tons, and still larger masses of meteoric iron have been found at several places in South America, where the dryness of the climate has preserved them from rusting. The meteoric iron found at Cape York in N. Greenland in 1897 was estimated to weigh about 100 tons.

It was formerly supposed that all iron is meteoric, but the Disco iron has been proved to be of terrestrial origin, for it is associated with a basalt containing iron disseminated in small nodules which are evidently constituents of the basalt.

Noteworthy Localities for Silver and Copper:

Silver and copper are usually found in metalliferous veins; the following two localities are remarkable and contribute typical specimens to most collections:—

Kongsberg (Norway).—Silver, not only in wiry and stringy masses, but also in very distinct crystals of cubic habit in calcite, with quartz, blende and galena; the silver is often transformed into argentite. It occurs in veins which are only productive of the metal and of silver ores where they intersect the so-called "fahlbands," which are gray belts of crystalline rock impregnated with metallic sulphides.

Lake Superior Mining Region.—Both copper and silver are here found under quite peculiar conditions. They occur together in basaltic rocks (melaphyres) which are accompanied by conglomerates and sandstones, in veins in the melaphyre and also in the amygdaloidal cavities of this rock; they are associated with quartz, calcite, prehnite, laumontite, analcite, datolite, natrolite, fluor, and other minerals. Sometimes the amygdaloidal cavities are almost entirely filled with copper, and a single nodule of metal may consist partly of silver and partly of copper. The crystals of calcite sometimes enclose copper. The twin groups of copper are often elongated along the twin plane, as shown in Fig. 432.

SECTION II

THE HALOIDS

FLUOR

Fluor.—Fluoride of calcium; CaF_2; Ca = 51·1, F = 48·9. Cubic, holosymmetric. Common form, cube.

$$A = \{100\}, h = \{310\}, t = \{421\}.$$

Interpenetrant twins; twin axis normal to (111). Cleavage {111}, perfect. Brittle. Fracture, sub-conchoidal. H = 4; G = 3·2. Purple. Streak, white. Lustre, vitreous. Transparent. Refraction very weak; $\mu = 1{\cdot}43$; dispersion weak. Fusible with difficulty. Decomposed by sulphuric acid.

With the above description compare crystals from **Weardale** (Durham).

Fluor, or fluor-spar (*Germ.* Flussspath, *Fr.* Chaux fluatée), is the only common mineral which contains the element fluorine in any large proportion. It was in this mineral that Scheele discovered fluorine in 1771, although glass had been etched by means of fluor-spar and sulphuric acid about a century earlier.

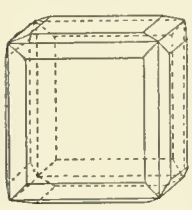

Fig. 434.—Fluor. Combination {100} {310}.

Fluor is found very widely distributed and in beautiful crystals. It was known in the early history of mining as a frequent associate of metallic minerals under the name *marmor metallicum* and was much valued as a flux; the name is derived from *fluo*, I flow.

The habit of fluor is remarkably constant; no mineral crystallises more persistently in cubes; other forms occasionally make their appearance, but the habit of the combinations is almost always the same. The cube sometimes has its edges bevelled by a four-faced cube $\{hk0\}$, generally {310}; more rarely truncated by the dodecahedron, as in some specimens from Redruth in Cornwall.

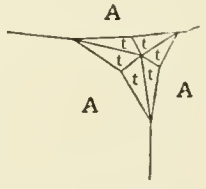

Fig. 435.—Fluor. Cube Corner with t {421}.

The octahedron is rare as a simple form; the well-known "rose-fluors," the pink crystals from Göschenen and Chamonix, are octahedra, as are also colourless crystals from Kongsberg in Norway and from Striegau in Silesia, and also the pink fluor found in the Island of Giglio near Elba. The edges of the octahedron are rarely truncated.

The low four-faced cube {310} occurs as a simple form; $\{hk0\}$ is so

rare in other minerals that it is sometimes known as the "fluoroid." This form is especially characteristic of certain violet-coloured crystals from Trevaunance Mine, St. Agnes, Cornwall, where it is combined with the cube. Other simple forms are rare; the dodecahedron and the three-faced octahedron {441} have both been recorded from Striegau in Silesia. The six-faced octahedron t {421} occurs only in combination, and replaces the corners of the cube (Fig. 435) in the large yellowish crystals from Menheniot in Cornwall.

The above instances illustrate the great variety of forms found in any mineral which has been closely studied, even though the common specimens (as in fluor) may be quite simple.

Fluor can be etched with hydrochloric acid, or with sodium carbonate; both solvents appear to give holosymmetric etched figures; the acid produces square hillocks and the alkali square pits on the cube faces. Cleavage plates etched with HCl sometimes show a partitioning into three sectors; this may, however, be only due to the growth of the crystal radially from its centre towards the cube faces; many substances show traces of such growth, so that they appear to consist of pyramids whose apices meet in the centre of the crystal. In fluor these "pyramids of growth" seem to be the six pyramids whose bases are the cube faces.

Twins are exceedingly common; two cubes are united by interpenetration according to the law —twin axis the cube diagonal (*i.e.* a line perpendicular to the face (111) or parallel to a dodecahedron edge), the corners of one cube projecting through the faces of the other. In these twins, at the exact point where an edge emerges, the cube face is often raised into a low pyramid consisting of four vicinal faces {*hk*0}, as mentioned on p. 97. They are shown in Fig. 436. The indices of these vicinal faces are very high, *e.g.* {32·1·0}.

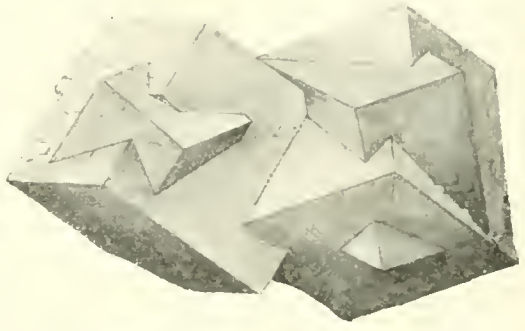

Fig. 436. Fluor. Twinned Groups of Cubes.

The faces of fluor are usually smooth and bright, with the exception of the octahedron, which is dull. Drusy and polysynthetic crystals are common. The drusiness of the octahedron and some other faces is often due to a polysynthetic growth of small cubes; an octahedron may consist of cubes large enough to be visible, as shown in Fig. 393; such polysynthetic growth need not interfere with the brightness of the *cube* faces, since they are composed of faces of the sub-individuals which all fall into the same plane.

Fluor presents a great variety of colour; colourless crystals are rare; yellow, blue, green and violet shades are common, and the rose fluors from Göschenen have been mentioned above. Amethystine and green fluors from the North of England and yellow from Saxony are common in museums. The colour is changed by heat and is supposed to be due to hydrocarbons, which may also account for a loss of weight

experienced by the coloured crystals when heated. The cubes are sometimes banded with layers of different colours parallel to the cube faces.

Most fluor exhibits a weak birefringence, which also varies in bands when the crystal is viewed between crossed nicols, and indicates lamellation parallel to the cube faces; a section parallel to (100) shows a square lamination, one parallel to (111) shows a triangular lamination.

No relation has been traced between the colour and composition of the mineral and there is no evidence that the birefringent laminæ are due to the alternation of isomorphous compounds or to zones of varying composition. Colourless (Swiss) crystals are free from birefringence.

Fluorescence derives its name from this mineral and is best shown by some of the richly coloured Cumberland specimens which appear amethystine or plum-blue by reflected and pale green by transmitted light.

The green and red crystals are strongly phosphorescent; the name "chlorophane" was given to certain fluors which phosphoresce in green colours, in the belief that they were a new mineral.

Owing to its low refractive power and slight dispersion, combined with the absence of pronounced birefringence, fluor is very valuable for optical purposes and is used in making "apochromatic" microscope objectives; but the colourless isotropic crystals are extremely rare.

Being almost the only substance which is not attacked by free fluorine, fluor-spar was used by Moissan for vessels and stoppers in his experiments on the isolation of fluorine. The presence of free fluorine has been established in a very dark violet fluor-spar from Quincié, Dept. du Rhône.

Fluor is readily distinguished from all other common minerals possessing a vitreous lustre by its very perfect octahedral cleavage.

Two unusual varieties of this mineral are—massive fluor, a compact substance without cleavage and having a splintery fracture; and earthy fluor, which is quite soft and lustreless.

The beautiful substance worked in Derbyshire as an ornamental material for vases, etc., under the name "Blue John," is a crystalline fluor which occurs lining metalliferous veins and consists of bands of varicoloured crystals.

Fluor is chiefly found as a vein-mineral associated with metallic ores, with barytes, calcite, etc.; it is also especially characteristic of those tin-bearing veins which are distinguished by the presence of the fluoriferous compounds, tourmaline, lepidolite, topaz, apatite, etc., and are supposed to be due to pneumatolysis or the action of vapours of tin fluoride (see p. 361).

No minerals are isomorphous with fluor except perhaps the $CaCl_2$, **hydrophilite**, found as a sublimation product at Vesuvius, which crystallises in small cubes.

Some Noteworthy Localities:

Weardale (Durham), and **Alston** (Cumberland).—Beautiful plum-coloured or green cubes, very frequently twinned by interpenetration, come from veins in the limestone, and the associated minerals may be quartz, calcite, pyrites, blende, galena, barytes, and chalybite. The calcite is generally in flat rhombohedra {110} with the prism {211}, and the chalybite or brown spar is also in similar flat rhombohedra. The barytes is in the white platy curved masses generally known as "cawk." The fluor is sometimes spangled over with glassy crystals of quartz, calcite, or chalybite.

Derbyshire.—From the lead mines come purple and lilac cubes, sometimes with a yellow centre, on vein quartz or crystallised calcite, associated with cubo-octahedra of galena and black blende; the calcite in prisms terminated by {110} or in the flat rhombohedra alone.

St. Agnes (Cornwall).—From the metalliferous veins in the slate (or "killas") in this tin-mining district, deep violet four-faced cubes {310} generally combined with small faces of the cube, upon dark crystallised chlorite with quartz and cubes of pyrites. The fluor is sometimes green below, and passes into deep violet on the surface.

Chamonix (Savoy).—Beautiful rose-red *octahedra* on smoky quartz with titanite and adularia.

Gersdorf (Saxony).—Transparent brown and yellow cubes are associated with groups of tabular barytes and small chalcopyrite crystals of tetrahedral habit.

The only haloids, in addition to fluor, which are at all common or important are some of the minerals belonging to the salt group, and the mineral cryolite.

THE SALT GROUP

Salt.—Chloride of sodium; NaCl; Na = 39·4, Cl = 60·6. Cubic. Common form, cubes. Cleavage {100}, perfect. Brittle. Fracture, conchoidal. H = 2½; G = 2·2. Colourless. Streak, white. Lustre, vitreous. Transparent. Refraction weak; $\mu = 1{\cdot}54$. Taste, saline. Fusible. Soluble in water.

With the above description compare crystals from **Wieliczka** (Poland).

Sylvite.—Chloride of potassium; KCl; K = 52·4, Cl = 47·6. Cubic; symmetry, holoaxial. Common form, cubes. Cleavage {100}, perfect. Brittle. Fracture, uneven. H = 2; G = 1·9. Colourless. Streak, white. Lustre, vitreous. Transparent. Refraction weak; $\mu = 1{\cdot}49$. Taste, saline, bitter. Fusible. Soluble in water.

With the above description compare crystals from **Stassfurt** (Prussia).

Rock Salt crystallises in cubes, generally without any modifications; good examples have come from Stassfurt in Prussia and from Wieliczka in Poland; octahedral crystals are comparatively rare.

The natural crystals differ considerably in appearance from those

which are obtained by the evaporation of brine in the salt-manufacture of Cheshire and other places; the latter are almost always skeletal cubes or hopper-shaped octahedral crystals formed by the aggregation of small cubes (*cf.* Fig. 393).

Sylvite (so-called from *sal digestivus sylvii*, the old pharmaceutical name for the salt) was first discovered as a volcanic sublimation at Vesuvius, but far finer specimens have been subsequently found associated with the salt deposits of Stassfurt and of Kalusz in Galicia; among these are crystals as perfect as those of salt and very much richer in faces. Twinning is almost unknown in these two minerals; but twin lamellæ have been noticed in salt.

Ordinary massive, fibrous or granular salt is mostly impure, containing magnesium chloride and sulphates of calcium and magnesium; and it may assume various tints of yellow, red, and blue; very remarkable is a deep blue variety from Stassfurt, to be seen in most collections, of which the colour has been ascribed variously to a lower chloride of sodium, to sulphur, and to an interference effect due to included cavities. It is true that Bunsen obtained a deep blue mass by fusing potassium with KCl, but there is no direct evidence that the blue colour of the rock salt is due to a lower chloride.

Both salt and sylvite are readily soluble in about three parts of water; the violet colour which sylvite should give to flame may be masked by the presence of sodium; but the two minerals may be easily recognised by their characteristic tastes combined with the perfect cubic cleavage. Both salt and sylvite show traces of birefringence.

Both minerals are highly diathermanous, and cleavage blocks of rock salt have for this reason been valuable in thermal experiments where it has been necessary to enclose gases, for instance, in a tube with transparent ends which transmit the heat-rays with facility.

Sal-ammoniac, NH_4Cl, occurs in white crystals as an incrustration upon lava at Mount Vesuvius.

Cerargyrite (horn silver, chlorargyrite), AgCl, like the bromide and iodide of silver, has a very characteristic horny appearance, often referred to by the authors of the sixteenth century, who describe a mineral which is transparent like the horn of a lantern. Crystals are rare, but cubes bearing faces of {110}, {111}, etc., are found, and are sometimes twinned on the octahedron face.

The haloids of silver are readily recognised by their adamantine lustre, horny appearance, and sectility; they readily fuse and yield a globule of metallic silver. Silver chloride is the compound precipitated by hydrochloric acid in solutions of silver salts; this may serve to remind the student that cerargyrite is insoluble in acids, but soluble in ammonia.

Like the silver compounds used in photography, this mineral is rapidly altered by exposure to light, turning to a dark colour; in nature it is found of many colours, gray, green, yellowish, and bluish.

The chlorine in all the minerals of this group may be detected by

the deep blue colour imparted to the oxidising flame when they are heated in a microcosmic bead saturated with oxide of copper.

The group includes a number of cubic chlorides, bromides and iodides of monovalent elements and of the radicle ammonium, and to these must also be added the cyanides and fluorides, since KCN, NH_4CN, NaF, KF, crystallise in the cubic system although they do not occur as minerals. Cubic isomorphous mixtures of the bromide, iodide, and chloride of silver are also known as minerals. On the other hand, AgI crystallises in the hexagonal system, but it becomes cubic in its properties when raised to a temperature of 146°, and a modification is also known which is cubic at ordinary temperatures; no doubt, therefore, the whole group must be regarded as dimorphous.

Octahedra of sal-ammoniac when etched by water develop facets of {875} displaying holoaxial symmetry. Sylvite treated in the same way gives similar facets of {931}, but the other members of the group behave as though holosymmetric. No crystals belonging to this group show rotatory polarisation, which might perhaps be expected from enantiomorphous symmetry.

CRYOLITE

Cryolite.—Fluoride of sodium and aluminium; Na_3AlF_6: Na = 32·8, Al = 12·8, F = 54·4. Anorthic.

$(110) : (1\bar{1}0) = 88° 2'$, $(001) : (110) = 89° 52'$, $(001) : (101) = 55° 17'$.

Cleavage {001}, perfect; {110} and {$\bar{1}$01}, nearly perfect. Brittle. Fracture, uneven. H = 2½; G = 3·0. Colourless. Streak, white. Lustre, vitreous. Transparent. Refraction weak; $\beta = 1{\cdot}36$. Birefringence weak, positive. Axial plane perp. to (010); acute bisectrix 44° 5′ to normal of (001), 11° 12′ to normal of (101); $2E = 59° 24'$; $\rho < v$. Easily fusible. Decomposed by sulphuric acid.

With the above description compare crystallised material from **Arksukfiord** (Greenland).

Cryolite is interesting as having been for a long time the only source of aluminium, and is still an important ore from which that metal is manufactured. There is a large bed of massive cryolite in gneiss at Ivigtut in Arksukfiord, (West Greenland), where it was discovered about 1795. It is a colourless or pure white substance, but is in parts coloured red or brown by ferric oxide. The surfaces of the cracks in the massive mineral are lined with the clear transparent crystals which resemble cubes with a pronounced cubic cleavage, and these are generally disposed in parallel positions. The mineral is easily proved to be a fluoride by the evolution of HF when it is heated with sulphuric acid,

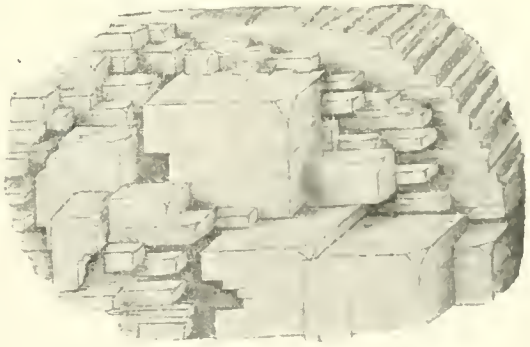

Fig. 437.—Cryolite.

and is distinguished from fluor by the nearly rectangular cleavage, the oblique striation (Fig. 437), and by the ready fusibility. Cryolite melts in the flame of a candle and received its name (κρύος, λίθος, ice-stone) from this characteristic. The crystalline system is difficult to determine, and for a long time it was doubtful whether the mineral is monoclinic or anorthic. Optical examination and etching with sulphuric acid show the crystals to be repeatedly twinned and to belong to the anorthic system, but the habit is monoclinic.

SECTION III

THE MONOSULPHIDES

THE GALENA GROUP

Galena.—Sulphide of lead ; PbS; Pb = 86·6, S = 13·4. Cubic, holosymmetric. Common form, cubo-octahedron.

$$A = \{100\},\ o = \{111\},\ d = \{110\},\ p = \{221\}.$$

Cleavage $\{100\}$, perfect. Almost sectile. Fracture, even. H = $2\frac{1}{2}$; G = 7·5. Lead-gray. Streak, lead-gray. Lustre, metallic. Opaque. Easily fusible, after decrepitation. Decomposed by nitric acid.

With the above description compare crystals from **Neudorf** (Harz).

Galena (*Germ.* Bleiglanz) is the common ore of lead, and argentiferous galena is of even greater value and importance as a profitable ore of silver. The name galena is used by Pliny. The mineral is a frequent constituent of metalliferous veins, where it sometimes occurs as fine crystals, usually cubes or cubo-octahedra (Figs. 438 and 442), and generally of cubic habit. At some localities, as at Neudorf in the Harz, the habit is octahedral, and the octahedron edges are bevelled by a series of planes $\{hhl\}$ which give the crystal quite a rounded appearance (Fig. 439).

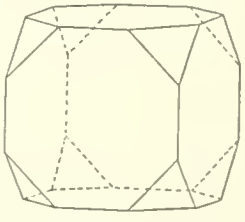

Fig. 438.—Galena. Cubo-octahedron.

The cube faces of galena often consist in reality of very flat vicinal

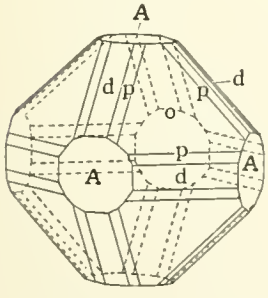

Fig. 439.—Galena, from Neudorf ; *o* {111}, A {100}, *d* {110}, *p* {221}.

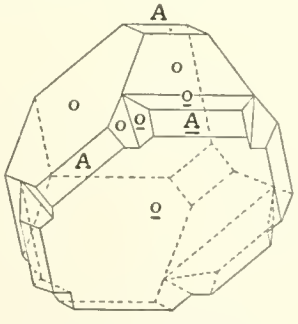

Fig. 440.—Galena, twinned on (111).

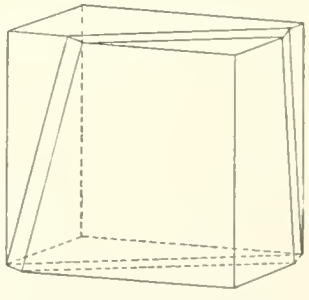

Fig. 441.—Galena with Twin Lamella (441).

faces, not only $\{hk0\}$ as in fluor, but also $\{hkk\}$; the latter replace each

cube face by four (nearly) square facets which almost fall into a plane. The faces of galena are rarely smooth or brilliant.

Twinning is not common, but sometimes takes place on the spinel type, the axis of twinning being the ditrigonal axis, and the plane of composition the octahedron face to which it is perpendicular; sometimes the individuals interpenetrate, as in Fig. 440; and in either case they are flattened along the plane of composition, so that the twin may present the appearance of one thin hexagonal plate lying upon another.

Crystals of galena are sometimes traversed by striæ and bands whose direction is shown in Fig. 441; these can be seen as nicked lines upon the cleavage surfaces and are supposed to be twin lamellæ parallel, usually, to (441), but also to other planes, such as (331) (311). Such lamellæ sometimes give quite a streaky appearance to massive galena; they are perhaps due to pressure, since glide-planes can be artificially produced in these directions by squeezing a crystal of the mineral.

The perfect cubic cleavage of galena is its most conspicuous feature. A very remarkable, though rare, variety which has now been found at several different localities possesses, not cubic, but perfect *octahedral* cleavage; this curious exception has not been satisfactorily explained; the crystals exhibiting octahedral cleavage have in most cases been found to contain from 1 to 2 per cent of Bi_2S_3; the cleavage is said to become cubic after the mineral has been heated, and the change takes place without decrepitation, which is all the more remarkable, (1) because ordinary galena decrepitates when heated, and (2) sudden changes in crystalline structure are not infrequently accompanied by decrepitation; it is also remarkable that no change in density is produced by the heating.

Galena is usually found granular and massive, sometimes almost compact (*Germ.* Bleischweif), but in almost all specimens the brilliant facets of the cubic cleavage are to be distinguished on a fractured surface and give the mineral a shining appearance. Experiments on the etching and the percussion figures of galena all confirm its apparently holosymmetric character.

Galena is easily recognised by the cubic cleavage, and the identification is confirmed by the softness, lead-gray colour, high density, and reduction on charcoal to a globule of lead. The cleavage is shown on the left-hand side of Fig. 442. Almost all galena contains silver, and although this does not often amount to more than one per cent, the mineral is one of the most profitable ores of silver.

A very remarkable occurrence is that at Commern in the Eifel, where galena is found in the Bunter sandstone as concretionary nodules of spherical shape.

Galena is sometimes tarnished blue; when decomposed, it generally gives rise to carbonate and sulphate, so that it is often accompanied by colourless crystals (as at Monte Poni, in Sardinia) or white earthy crusts of cerussite and anglesite.

In the lead mines of Huelgoat in Brittany, and in Wheal Hope, near Truro, in Cornwall, were formerly found large hexagonal prisms

consisting of galena; these are crystals of lead phosphate which have been converted into sulphide, in other words, *pseudomorphs* of galena after pyromorphite.

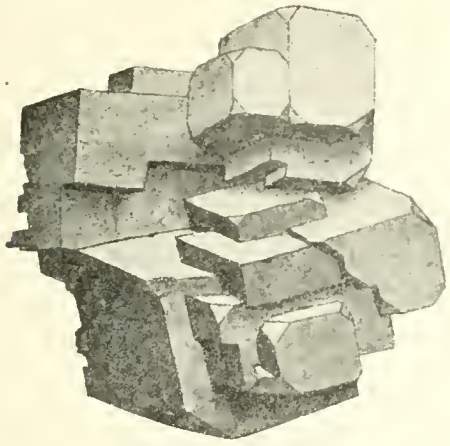

Fig. 442.—Galena, from Joplin, Missouri.

Fig. 443.—Galena on Chalybite, from Neudorf (British Museum).

Some Noteworthy Localities:

Derbyshire (and the North of England).—Crystals of cubic habit, generally cubo-octahedra, associated with calcite, fluor, quartz, blende, pyrites, and barytes, in veins traversing limestone. These veins are, and have long been, worked as lead mines.

Neudorf (and other localities) in the Harz district.—Crystals of octahedral habit and "spinel twins," associated with quartz, calcite, chalybite (in smooth brown rhombohedra {100}), fluor, chalcopyrite, and blende, also bournonite and tetrahedrite, in veins traversing clay slates (Fig. 443); the galena is argentiferous.

Jasper County (Missouri).—At the Joplin mines, fine cubes, with octahedron faces, upon a white or pink crystallised dolomite; with ruby-coloured blende, and chalcopyrite in small crystals of tetrahedral habit which are usually situated on the blende.

Argentite.—Sulphide of silver; Ag_2S; Ag = 87·1, S = 12·9. Cubic. Common form, cube. Cleavage {100} {110}, imperfect. Sectile. Fracture, sub-conchoidal. H = 2½; G = 7·3. Dark lead-gray. Streak, the same, shining. Lustre, metallic. Opaque. Fuses readily and yields sulphurous fumes.

With the above description compare crystals from **Kongsberg** (Norway).

Argentite, the only important member of the cubic series in addition to galena and blende, sometimes occurs in rude, uneven cubes or octahedra, but is more usually platy, earthy, dendritic, etc.; it is generally converted on the surface, like many other silver ores, into an earthy black sulphide of silver. It is an important ore of silver and sometimes sufficiently abundant to be largely worked as such, *e.g.* in Nevada and in Mexico. The mineral is easily recognised by its sectility and shining streak, and by the bead of silver yielded by reduction on

charcoal; it could only be confused with rare sulphides and selenides of silver, mercury, and copper, of which several exist; but it does not itself contain either selenium, mercury, or copper.

THE BLENDE GROUP

Blende.—Sulphide of zinc; ZnS; Zn = 67, S = 33. Cubic. Symmetry, ditesseral polar. Common forms, {110} with tetrahedron. Twinned on (111).

$d = \{110\}$, $m = \{311\}$, $A = \{100\}$, $o = \{111\}$, $\omega = \{\bar{1}11\}$.

Cleavage {110}, perfect. Brittle. Fracture, conchoidal. $H = 3\frac{1}{2}$; G = 4. Yellow. Streak, pale yellow. Lustre, adamantine. Sub-transparent. Refraction very high; $\mu = 2{\cdot}37$. Fusible with difficulty. Decomposed by hydrochloric acid.

With the above description compare crystals from **Kapnik** (Hungary).

Blende, the most important ore of zinc, is an extremely common mineral, especially as a constituent of metalliferous veins. The name,

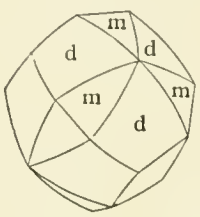

Fig. 444.—Blende, d {110} with m {311}.

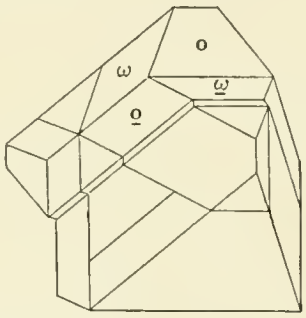

Fig. 445.—Blende, Spinel Twin.

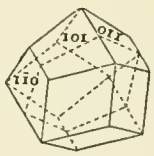

Fig. 446.—Blende, twinned on (111).

a German mining term signifying "blind" or "deceptive," was originally given to this substance as a metallic ore which resembled galena but yielded no lead; its other modern name, sphalerite, is a translation of blende ($\sigma\phi\alpha\lambda\epsilon\rho\acute{o}s$, deceptive). Although no longer likely to be mistaken for galena if attention be paid to the cleavage, blende is so variable in colour and appearance that it often deceives the eye and is difficult to recognise.

The common black crystals are combinations of the dodecahedron {110} with rounded faces of {311} (Fig. 444). The green and yellow crystals from Hungary display faces of the dodecahedron, tetrahedron, cube, and other forms. Simple tetrahedral crystals are rare; black tetrahedra were formerly found in some of the mines in the St. Agnes district in Cornwall; they sometimes have their edges truncated by the cube, and their corners by the complementary tetrahedron. Whenever the two tetrahedra occur together one is smooth and bright, while the other is striated or dull. These two forms may also be distinguished by etching with hydrochloric acid (Fig. 447).

At most localities the crystals of blende are traversed by twin lamellæ parallel to the tetrahedron faces. Sometimes simple twin crystals of the spinel type of octahedral habit are found; in these the

bright faces of the tetrahedron $o\ \{111\}$ on one individual are opposite to the dull faces of the other tetrahedron $\omega\ \{\bar{1}\bar{1}\bar{1}\}$, (Fig. 445), so that the twinning is to be described as hemitropy about the ditrigonal axis, and not as reflection over the tetrahedron face to which that axis is perpendicular. Even in a "spinel" twin of this sort each individual is often traversed by twin lamellæ parallel to the other tetrahedron faces. In a twinned dodecahedron the six faces of one individual which are parallel to the twin axis coincide with six faces of the other individual (Fig. 446), so that the twinning may at first sight be overlooked; but complementary twinning such as would confer a holosymmetrical aspect on the crystals, as in diamond, is not found in blende. In addition to etching, pyroelectric experiments have proved the polar nature of the trigonal axes of blende; if an insulated plate cut perpendicular to one of these axes be brought into contact with heated metal it becomes positively or negatively electrified at the point of contact, according as the one face or the other is experimented on; the electrification is observed by means of an electrometer connected with the heated metal.

Fig. 447.—Blende $\{111\}$, $\{\bar{1}\bar{1}\bar{1}\}$, $\{100\}$, etched.

The perfect dodecahedral cleavage (angles of 60°) and adamantine lustre serve to distinguish blende from the minerals which it resembles; the black varieties may at first glance be mistaken for hornblende, which has nearly the same cleavage angle.

Blende is very commonly found massive, botryoidal, and curvilaminar; the curvilaminar and reniform varieties are known in Germany as "schalenblende" and "leberblende" respectively. Most of the *fibrous* varieties of zinc sulphide, on the other hand, may be recognised under the microscope as birefringent, and are in reality the hexagonal wurtzite (see p. 321). Blende itself is usually quite isotropic.

Most specimens contain iron, to which the great variety of colour is probably due; the black blende contains a considerable proportion; this appears to be an isomorphous intermixture of FeS, which may be present to the extent of 15 or 20 per cent. Indium and gallium were both discovered in blende, and the mineral may also contain manganese, cadmium, thallium, and tin. Absolutely pure blende, such as that from Franklin (New Jersey), known as "cleiophane," is colourless.

The mineral is remarkably free from alteration or tarnish, but is sometimes converted into white earthy sulphate or carbonate.

The zinc in blende is detected by the sublimate on charcoal in the reducing flame (Table E, p. 549), but the mineral may also yield a coating of cadmium oxide; sulphur is found by heating in the open tube; iron will generally be indicated by the borax bead after roasting.

Blende is a very common occupant of metalliferous veins, especially in association with galena, chalcopyrite, and other sulphides, with barytes, with fluor, and with quartz.

Some Noteworthy Localities:

Alston Moor, and other places in the lead mining districts in the north of England. Black lustrous blende (known locally as "black jack") occurs in veins and cavities ("flats") of the mountain limestone associated with quartz, calcite, galena, pyrites, fluor, and barytes; the blende is in curved crystals of the habit of Fig. 444. Especially fine are the groups which are accompanied by rounded or crested aggregations of white tabular barytes (locally known as "cawk").

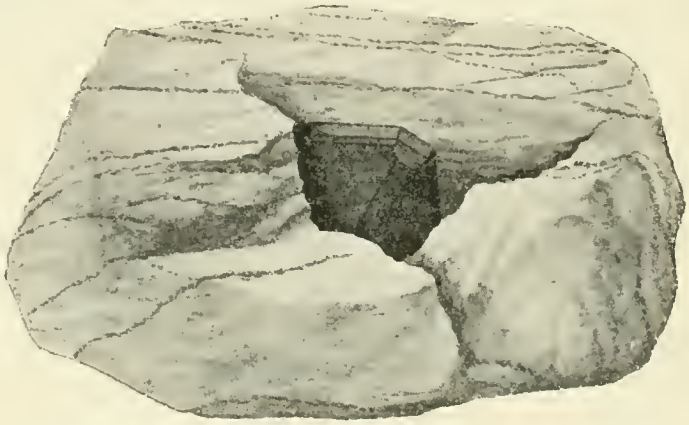

Fig. 448.—Blende, in Dolomite, from Binnenthal.

Binnenthal (Switzerland).—Small cracks in the snow-white dolomite contain brilliant brown tetrahedra of blende accompanied by equally brilliant crystals of galena, scarlet realgar, and other metallic sulphur compounds. The blende is sometimes in crystals of cubo-octahedral habit, showing frequent twin laminæ. The dolomite is traversed by thin bands of crystallised iron pyrites, as shown in Fig. 448.

Schemnitz and other localities in the gold and silver mining districts of Hungary.—Metalliferous lodes in propylite and other rocks contain pale yellow and greenish blende in complex crystals of dodecahedral habit, much laminated, and associated with quartz (often amethyst) of trigonal habit (Fig. 501, p. 371), argentiferous galena, pyrites, and chalcopyrite. See also the description of tetrahedrite from **Kapnik** (p. 342).

THE MILLERITE GROUP

Millerite.—Sulphide of nickel; NiS; Ni = 64·6, S = 35·4. Hexagonal.

$a : c = 1 : 0{\cdot}988.$

Brittle. H = $3\frac{1}{2}$; G = 5·5. Brass-yellow. Streak, greenish-black. Lustre, metallic. Opaque. Easily fusible. Decomposed by nitric acid.

With the above description compare acicular crystals from **Merthyr Tydvil** (Glamorganshire).

Niccolite.—Arsenide of nickel; NiAs; Ni = 43·9, As = 56·1. Hexagonal.

$a : c = 1 : 0{\cdot}819.$

Brittle. Fracture, uneven. H = $5\frac{1}{2}$; G = 7·5. Copper-red. Streak, brownish-black. Lustre, metallic. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystallised material from **Sangerhausen** (Prussian Saxony).

Millerite, capillary pyrites (*Germ.* Nickelkies, Haarkies).

Niccolite, nickeline, copper nickel (*Germ.* Rothnickelkies, Kupfernickel).

The two minerals described above are easily recognised, millerite by its brassy colour, and by the fibrous or acicular structure (which is very unusual among the other yellow metallic sulphides). The finest acicular crystals, like hairs, occur in cavities of the clay ironstone at Merthyr Tydvil; fibrous velvety masses are worked at the Gap mine in Lancaster County, Pennsylvania. The mineral yields the reaction for nickel in the borax bead; but it generally contains also copper, iron, and cobalt, which may partially mask this reaction.

Niccolite is recognisable by its remarkable bronzy or "pinchbeck" colour, which is quite unlike that of any other mineral except breithauptite and copper arsenide; the presence of arsenic and nickel (Tables B, C, G, p. 548) is easily proved, and the mineral may also contain Sb, S, Fe, Co; and as the proportion of antimony increases it gradually passes into breithauptite.

The isomorphous minerals belonging to this hexagonal group are remarkably different in their characters. Millerite only occurs in acicular or capillary crystals of extreme thinness seldom terminated, or in fibrous aggregates; niccolite is rarely crystallised, and then in imperfect hexagonal pyramids, of which only the terminations are developed. To the same group belong the following:—

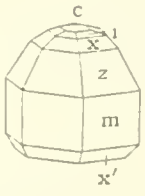

Fig. 449.—Greenockite: m {1010}, z {2021}, x {1011}, i {1012}, C {0001}, x' {1011}.

Greenockite, CdS, which is a rare mineral found as little hemimorphic pyramidal crystals (Fig. 449) dispersed on prehnite from the Glasgow and Greenock tunnel near **Bishopton** in Renfrewshire. C = {0001}, i = {01$\bar{1}$2}, x = {01$\bar{1}$1}, z = {02$\bar{2}$1}, m = {01$\bar{1}$0}.

Covellite, CuS, a blue microcrystalline mineral.

Wurtzite, the "fibrous zinc blende," ZnS, resembles blende, but may be recognised by its birefringence. Crystals are extremely rare, but black terminated prisms having the form of greenockite (Fig. 449) have been found at Oruro in Bolivia, and their angles are near those of greenockite.

Breithauptite, NiSb, occurs as little prisms of bronzy colour.

THE COPPER-GLANCE GROUP

Copper-glance.—Sulphide of copper; Cu_2S; Cu = 79·8, S = 20·2. Orthorhombic.

$$a : b : c = 0{\cdot}582 : 1 : 0{\cdot}970.$$

C = {001}, e = {023}, z = {113}.

$Ce = 32°\ 53'$, $Cz = 32°\ 44'$.

Twinned on (110), on (032), and on (112). Cleavage {110}, imperfect. Sectile. Fracture, conchoidal. H = 2½; G = 5·7. Lead-gray. Streak, black. Lustre, metallic. Opaque. Easily fusible. Decomposed by nitric acid.

With the above description compare crystals from **Redruth** (Cornwall).

Copper-Glance, redruthite, chalcocite, vitreous copper (*Germ.* Kupfer-glanz), is a good example of an orthorhombic mineral with pseudo-hexagonal symmetry, the prism angle being near 60°; like aragonite and chrysoberyl, it still further simulates the symmetry of the hexagonal system by twinning about the prism planes; and it exhibits a great variety both of form and twinning.

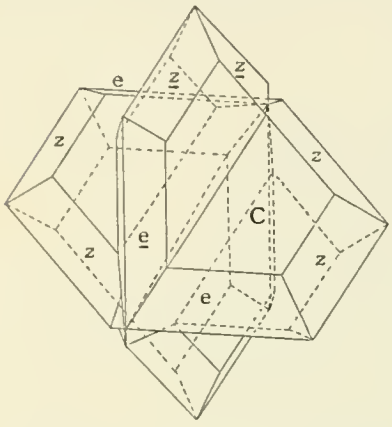

Fig. 450.—Copper-glance twinned on (112); C {001}, *e* {023}, *z* {113}.

Characteristic among Cornish varieties are flat-topped prisms from Redruth, thin plates and stout drusy prisms from St. Ives, and inter-penetrating twins consisting of two tabular crystals intersecting at an angle of 69° from St. Just.

The pseudo-hexagonal twins and triplets resemble those of chrysoberyl, and are distinguished by striæ on the basal plane parallel to B (010), (*cf.* Fig. 519, p. 386). Very similar specimens are found at Bristol, Connecticut.

The intersecting twins have either (112) for twin plane, when they cross at angles of 87° 54′ (Fig. 450), or are twinned on (032), when the angle $C\underline{C}$ is 69°; the form (032) is not found as a face on any of the crystals. Copper-glance occurs largely both massive and compact, and is of a dark gray metallic colour, with sometimes a rather greasy lustre. On exposure it blackens (owing to surface alteration into melaconite (?)); it is also liable to tarnish, and becomes converted into covellite, the blue sulphide, or into erubescite (see p. 339). Being somewhat sectile it might be confused with argentite, and the form of the crystals makes it somewhat resemble stephanite, but the bead of copper obtained by reduction on charcoal (Table F, p. 550), instead of silver, serves to distinguish it from those minerals. It sometimes contains a little iron.

Acanthite, the other mineral belonging to the orthorhombic group, has been found in the silver mines of Freiberg in Saxony; it possesses all the chemical characters of the cubic mineral argentite, which belongs to the galena group, but occurs in long blade-shaped crystals; it has been suggested that these are merely mis-shapen crystals of argentite.

Under **stromeyerite** are classed certain silver ores which may be called argentiferous copper-glance: *i.e.* isomorphous mixtures of copper-glance and acanthite; but as these ores are rarely crystallised, it is difficult to refer them to this group with certainty; orthorhombic crystals having such a composition are certainly known.

CINNABAR

Cinnabar.—Sulphide of mercury ; HgS ; Hg = 86·2, S = 13·8. Hexagonal ; symmetry, trigonal holoaxial (quartz class). Common form, rhombohedron with basal pinakoid. Cleavage, the prism $\{2\bar{1}1\}$, good. Sectile. Fracture, uneven. H = $2\frac{1}{2}$; G = 8·2. Cochineal-red. Streak, vermilion. Lustre, metallic adamantine. Subtransparent. Refraction very strong ; $\omega = 2{\cdot}85$. Birefringence positive, very strong ; $\epsilon - \omega = 0{\cdot}35$. Circular polarisation very strong. Volatile. Decomposed by nitric acid.

With the above description compare crystals from **Almaden** (Spain).

Cinnabar (*Germ.* Zinnober) is remarkable for its enormous refractive power, and strong birefringence, but still more for the remarkable circular polarisation, which, as in quartz, is associated with trigonal holoaxial symmetry ; the rotatory power of cinnabar is no less than fifteen times that of an equal thickness of quartz ; the plane of polarisation of red light is rotated through about 325° by a plate 1 mm. thick. Faces $\{hkl\}$ which display the true symmetry are rare : the form $\{621\}$ has been observed. The crystals are often twinned on the basal plane (111), and then show Airy's spirals when viewed in the direction of the principal axis in convergent light.

The mineral is more often found massive or earthy, and then has a rich vermilion colour ; much of the ore from Idria in Carniola is mixed with impurities and is brown and slaty. Cinnabar may always be recognised by its true vermilion streak, which is sufficient to distinguish it from cuprite, realgar and proustite, though the latter mineral resembles it somewhat both in colour, lustre, and streak. The deposition of mercury on heating either in the open tube alone, or in the closed tube with sodium carbonate, affords confirmatory evidence.

SURVEY OF THE MONOSULPHIDES

The monosulphides (arsenides, etc.) form an interesting series, crystallising in three systems in isomorphous groups, of which the principal members are the following :—

Cubic.	Hexagonal.	Orthorhombic.
	I.	
Blende ZnS	Wurtzite ZnS	
Alabandite MnS		
Troilite FeS		
	Greenockite CdS	
	Millerite NiS	
	Niccolite NiAs	
	Breithauptite NiSb	

Cubic.	Hexagonal.	Orthorhombic.
	II.	
Galena PbS		
Argentite Ag_2S		Acanthite Ag_2S
		Stromeyerite $(Cu, Ag)_2S$
Artificial Cu_2S		Copper-glance Cu_2S
	III.	
Metacinnabarite HgS	Cinnabar HgS	

Of these the orthorhombic minerals are all pseudo-hexagonal, so that the connection is even more close than at first sight appears.

FeS in the cubic form has been prepared artificially, and also enters into the composition of blende. The compound FeS is found as a brassy substance (troilite) in some meteorites. It is not certain whether this is cubic or whether it is hexagonal and identical with the mineral pyrrhotite described on p. 339.

NiS in the cubic form appears in a mineral, **Pentlandite** (Fe, Ni)S, which, though not well crystallised, has an octahedral cleavage.

Both the selenides and tellurides of lead and silver are found as cubic minerals and belong to the same series with galena; Ag_2S is proved to be dimorphous by its occurrence as an isomorphous mixture with Cu_2S in stromeyerite, even if the orthorhombic modification known as acanthite be not really isomorphous with copper-glance. Cu_2S is obtained in octahedra as a fusion product in copper furnaces.

Among these minerals blende and alabandite are undoubtedly ditesseral polar (tetrahedral), but galena and argentite apparently holosymmetric; cinnabar is trigonal holoaxial (quartz class) and has different dimensions from those of greenockite, which is dihexagonal polar; wurtzite is occasionally found well crystallised in the zinc furnaces, and the crystals are dihexagonal polar and completely isomorphous with greenockite.

The monosulphides therefore fall naturally into three isodimorphous series, the first comprising the zinc group, the second the lead group, and the third the mercury sulphides.

SECTION IV

THE DISULPHIDES

THE PYRITES GROUP

Pyrites.—Sulphide of iron ; FeS_2 ; Fe = 46·6, S = 53·4. Cubic ; symmetry, tesseral central. Common forms, cube, octahedron, pyritohedron {210}.

$A = \{100\}$, $o = \{111\}$, $d = \{110\}$, $e = \{210\}$, $t = \{421\}$, $s = \{321\}$.

Supplementary twins. Brittle. Fracture, conchoidal. H = 6 ; G = 5·1. Pale brass-yellow. Streak, greenish-black. Lustre, metallic. Opaque. On charcoal, burns, and gives off sulphurous fumes. Fuses to magnetic globule. Decomposed by nitric acid.

With the above description compare crystals from the **Island of Elba.**

Pyrites (*Germ.* Eisenkies, or Schwefelkies, *Fr.* Fer sulfuré) is one of the commonest and most ubiquitous of minerals ; as small crystals and

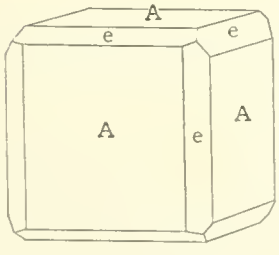

Fig. 451.—Pyrites, *a* {100}, *e* {210}.

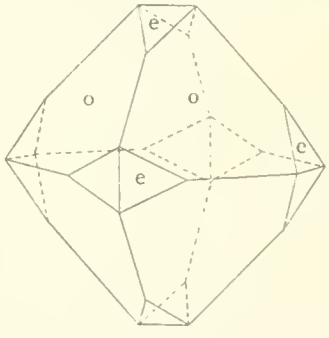

Fig. 452.—Pyrites, *a* {111}, *e* {210}.

specks of a brassy-yellow colour it may be noticed in all manner of rocks from basalts to slates ; as lustrous cubes and cubic combinations it is very frequent in metalliferous veins. By the ancients it was not distinguished from chalcopyrite, and the name pyrites as used by Dioscorides and Pliny (first century A.D.) includes several minerals, which (as implied by the name) yield sparks when struck with the hammer ; perhaps not only sulphides, in which the sparks are due to the combustion of the mineral itself, but also hard minerals, like flint or emery, in which the sparks are due to the combustion of the metal of the hammer.

Pyrites is the best known and most typical example of tesseral centrosymmetry (or, as it is sometimes called, "parallel-faced hemihedrism")

in the cubic system. It commonly occurs in simple cubes, but even these generally betray their true symmetry by the well-marked striations (Fig. 82, p. 43), which are parallel to alternate pairs of edges ; the striations on each face being therefore at right angles to those upon the adjacent faces ; these are due to an oscillatory combination of the cube with {210} (see p. 248). Other simple forms are : the octahedron, whose faces are generally smooth and bright ; and the pentagonal dodecahedron {210}, which is so characteristic of this mineral that it is often called the pyritohedron ; the dodecahedron, on the other hand, is conspicuous by its rarity. Numbers of forms occur in combination. Among the combinations the form {421} is easily recognised because its edges are truncated by {210} ; {321} replaces the edge *oe* (Fig. 457) : and {210} is generally present. The octahedron may often be recognised as a small bright triangular face truncating the corner of {210} (Fig. 457) and is sometimes laminar in structure. The two supplementary pyrito-

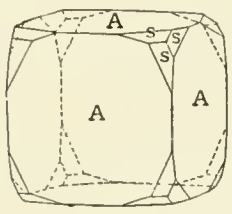

Fig. 453.—Pyrites, A {100}, *s* {421}.

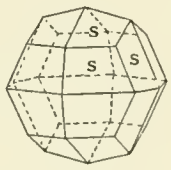

Fig. 454.—Pyrites, *s* {421}.

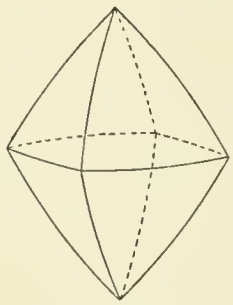

Fig. 455.—Pyrites, misshapen, from French Creek.

hedra {210} and {120} which would make up a four-faced cube (Fig. 27) are rarely, if ever, found together. There is nothing in the shape to distinguish the pyritohedron {210} from the supplementary pyritohedron {120}.

Very remarkable are the crystals from French Creek Mines in Pennsylvania, which have the aspect of simple *tetragonal bipyramids* (Fig. 455) ; these are explained as due to the development of eight faces belonging to the three-faced octahedron {332} ; some of the crystals even resemble orthorhombic bipyramids. Another example of misshapen pyrites is afforded by thin rod-like crystals from Lobenstein, in Thüringen ; these are elongated cubes. Twinning is rare, but brown pyritohedra found in marl at Minden in Prussia are beautiful examples of supplementary twinning (*Germ.* "Zwillinge des eisernen Kreuzes"), one crystal projecting entirely through the other (Fig. 456) ; they may be described as twinned by reflection over any face of {110}.

It has been noticed that some pyritohedra have their faces striated parallel to the cube edges (Fig. 457), and others (more rare) perpendicular thereto. Now it has also been proved that the former when warmed in contact with a copper wire give rise to an electric current which travels from the copper to the pyrites, or are thermo-electrically positive, whereas the latter are thermo-electrically negative or give rise

to a current in the opposite direction. The difference is very great, one sort of crystal being more positive in this respect than antimony, and the other sort more negative than bismuth; some pyrites crystals consist in part of positive and in part of negative material.

It is possible that apparently simple crystals are, like diamond, really supplementary twins, and that the true symmetry of pyrites is that of the ullmannite class, tesseral polar. This suggestion is confirmed by the *tetrahedral* habit of some artificial crystals of pyrites. It is true that the figures produced by etching with *aqua regia* are symmetrical about the cube planes, but, as in diamond, this might be the case with a completely interpenetrant supplementary twin.

Iron pyrites is generally recognisable by its appearance; it is distinguished from chalcopyrite by the paler colour, the superior hardness, and the streak; pyrrhotite, the only other mineral with which it might be confused, is always of a pinchbeck-bronze colour and is slightly magnetic. Some varieties of pyrites seem to be more liable to

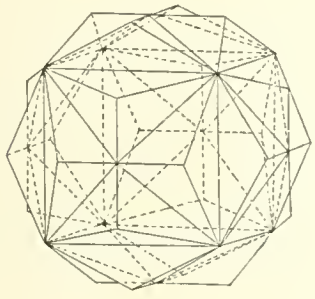

Fig. 456.—Pyrites, {210}, supplementary twin.

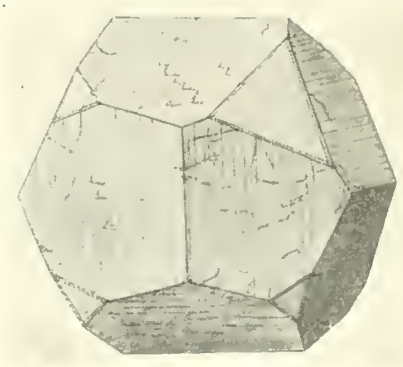

Fig. 457.—Pyrites, {210}, {111}, {321}, from Elba.

decomposition than others; this is probably due to their containing marcasite, which has the composition of pyrites but is a far less stable compound; the fibrous and stalactitic forms in particular become converted into iron sulphates and liberate sulphuric acid; some of these consist largely of marcasite. Ordinary pyrites is often converted into limonite and appears quite dark on the surface: this is the case, for example, with the twin crystals from Minden.

Pyrites sometimes contains nickel, cobalt, or copper: the first two, doubtless, as isomorphous intermixtures of the corresponding sulphides, the latter probably as chalcopyrite; silver and thallium are also sometimes present. But the most important impurity is gold, which often occurs disseminated minutely through crystallised pyrites and in sufficient quantity to render the mineral one of the chief sources of gold, just as argentiferous galena is one of the chief sources of silver. In pyrites, however, the gold is not present as an isomorphous compound, but as the metal. A large quantity of gold is extracted from auriferous pyrites in various parts of the world: in the Rossland district of

British Columbia, for instance, auriferous pyrites and chalcopyrite are largely worked. Much of the free gold in nature may have been originally derived from pyrites.

The chief commercial use of pyrites is for the manufacture of sulphuric acid and sulphur, and the ferric oxide obtained as a by-product in this process is used as rouge and polishing powder; some of the varieties which contain much chalcopyrite are also worked as copper ores. The alum shales so largely used in the manufacture of alum are merely shales which are richly impregnated with pyrites and marcasite.

Pyrites often occurs massive or in nodular and stalactitic forms: the latter especially when it has resulted from the decomposition of organic materials. Fossils may consist of pyrites, and in such cases the mineral has doubtless been produced by reduction of solutions of ferrous sulphate through the action of the decaying organism. This may have been the origin of many nodules of pyrites and marcasite found in chalk and clay. The liberation of sulphuric acid by the subsequent decomposition of the pyrites, and its action upon limestone, would account for the origin of gypsum by which such fossils and nodules are often accompanied.

Some Noteworthy Localities:

Traversella (Piedmont).—Some of the finest specimens are from the iron mines of the Chiusella Valley, where the chief ore is a crystalline magnetite, and in druses of this mineral occur sometimes quite large isolated crystals and groups of pyrites. These are pyritohedra and combinations with cube, octahedron, and $\{hkl\}$, often associated with quartz and pearl-spar.

Island of Elba.—Equally perfect are the crystals from the iron mines of Rio, where they occur in connection with hæmatite deposits in a siliceous slate; the pyrites is very rich in faces and varied in habit (especially pyritohedral), often enclosing hæmatite, and sometimes altered to limonite.

Cornwall.—Generally in simple striated cubes with chalcopyrite or quartz in metalliferous veins traversing clay-slate, and often associated with chlorite.

The following minerals belong to the pyrites group and crystallise in the same forms and combinations.

Chloanthite.—Arsenide of nickel; $NiAs_2$; Ni = 28·1, As = 71·9. Cubic: symmetry, tesseral central. Common form, cubo-octahedron. Cleavage $\{111\}$, imperfect. Brittle. Fracture, uneven. H = $5\frac{1}{2}$; G = 6·5. Tin-white. Streak, grayish-black. Lustre, metallic. Opaque. Easily fusible. Soluble in nitric acid.

With the above description compare crystals from **Riechelsdorf** (Hesse).

Smaltite.—Arsenide of cobalt; $CoAs_2$; Co = 28·2, As = 71·8. Cubic; symmetry, tesseral central. Common form, cubo-octahedron. Cleavage $\{111\}$, imperfect. Brittle. Fracture, uneven. H = $5\frac{1}{2}$; G = 6·2. Tin-white, slightly

steel-coloured. Streak, gray-black. Lustre, metallic. Opaque. Easily fusible to a magnetic globule. Decomposed by nitric acid.

With the above description compare crystals from **Schneeberg** (Saxony).

Cobaltite. — Arseno-sulphide of cobalt; CoAsS; Co = 35·5, As = 45·2, S = 19·3. Cubic; symmetry, tesseral central. Common form, pyritohedron with cube. Cleavage {100}, fair. Brittle. Fracture, uneven. H = 5½; G = 6·2. Silver-white, slightly reddish. Streak, grayish-black. Lustre, metallic. Opaque. Fusible to magnetic globule. Decomposed by nitric acid.

With the above description compare crystals from **Tunaberg** (Sweden).

The above three minerals closely resemble pyrites in their crystal characters. **Cobaltite** (*Germ.* Kobaltglanz) is found in very perfect octahedra, cubes, and pyritohedra, and their combinations, at Tunaberg in Sweden, in limestone in a gneiss, together with copper pyrites and other metallic ores. **Smaltite** (*Germ.* Speiskobalt) and **chloanthite** (*Germ.* Weissnickelkies) crystallise in imperfect cubes and cubo-octahedra, but are more usually massive, and sometimes, as in Saxony and Bohemia, reticulated. The thermo-electric characters of these minerals appear to be the same as those of pyrites. Smaltite and chloanthite graduate into each other by isomorphous intermixture, different specimens containing different proportions of cobalt and nickel; they usually contain also sulphur and iron. Smaltite and cobaltiferous chloanthite are the common ores of cobalt and nickel.

All these minerals, owing to decomposition and oxidation, are liable to be accompanied by the corresponding sulphates and arsenates; these give a green colour to the nickel, and a pink colour to the cobalt compounds, by which they may often be recognised and distinguished.

THE MARCASITE GROUP

Marcasite.—Sulphide of iron; FeS_2; Fe = 46·6, S = 53·4. Orthorhombic, holosymmetric.

$$a : b : c = 0{\cdot}766 : 1 : 1{\cdot}234.$$

$$m = \{110\}, \; C = \{001\}, \; l = \{011\}, \; r = \{013\}.$$

$$mm = (110) : (1\bar{1}0) = 74^\circ\ 55', \; Cl = (001) : (011) = 50^\circ\ 59'.$$

Twinned on (110), less frequently on (101). Cleavage {110} imperfect, {011} very imperfect. Brittle. Fracture, uneven. H = 6; G = 4·8. Pale brass-yellow. Streak, greenish-gray.. Lustre, metallic. Opaque. Reactions like those of pyrites. Decomposed by nitric acid.

With the above description compare crystallised groups from **Folkestone** (Kent).

Marcasite (*Germ.* Strahlkies) is not often found in simple crystals, but, owing to its multiple twinning, presents a great variety of shapes with jagged outlines and re-entrant angles, and has in consequence received many trivial names; such are "Cockscomb Pyrites" (Kammkies), of which the specimens from Tavistock in Devonshire may be taken as an example, and "Spear Pyrites" (Speerkies), familiar

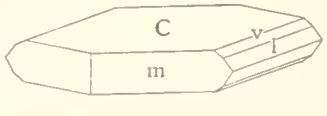

Fig. 458.—Marcasite. *m* {110}. C {001}, *l* {011}, *r* {013}.

as angular groups in the chalk of the south of England. These shapes are all due to twinning on (110).

Generally speaking, marcasite, as contrasted with its isomer, pyrites, is much more apt to occur in fibrous, radiated, and concretionary forms, and comparatively seldom in distinct crystals. "Radiated Pyrites" (Strahlkies) and "Hepatic Pyrites" (Leberkies) were names given to these varieties at a time when marcasite and pyrites were not distinguished as two minerals. The name marcasite is from an Arabic word used for crystallised pyrites of any sort during the middle ages.

Marcasite is very liable to decomposition; it is often converted on the surface into brown limonite; many specimens readily fall to pieces, especially when exposed to a moist atmosphere; the mineral becomes covered with efflorescent and fibrous growths of white ferrous sulphate, and the cabinets in which the mineral is kept contain free sulphuric acid. Many suggestions have been made as to the possible difference of constitution between pyrites and marcasite and the inferior stability of the latter. Since marcasite heated in a sealed tube to 200° with copper sulphate solution yielded a solution entirely ferrous, while pyrites yielded a solution of which 19·9 per cent was ferrous and the rest ferric, it has recently been proposed that marcasite is $Fe''S_2$ and pyrites $4Fe'''S_2 . Fe''S_2$. An earlier view concerning the easy decomposition of marcasite was that the mineral contained FeS, the unstable compound which is found as troilite in meteorites.

It is noteworthy that pyrites has been prepared artificially but marcasite has not. In nature marcasite occurs under much the same conditions as pyrites, but is not such a common mineral in the crystalline rocks and schists, or in metalliferous veins; it is more common than pyrites in the form of nodules and concretions of organic origin in sedimentary rocks.

A Noteworthy Locality:

Folkestone (Kent).—In chalk marl, here and at Dover, are found flat spear-headed groups (Fig. 459) locally supposed to be the heads of Roman weapons.

Fig. 459.—Marcasite in Chalk, from Dover.

These are twinned by repeated reflection across different faces of the prism {110}; as in aragonite (p. 94), repetition with inclined twin planes gives a stellate group of four or five crystals arranged about a centre, and so the form of Fig. 459. The striated faces which meet to form the ribs are the brachy-prisms {011} and {013}. The angle of the prism is nearly that of the pentagon; this accounts for the frequency of a pentagonal grouping of marcasite as contrasted with the hexagonal grouping of aragonite.

Mispickel.—Arseno-sulphide of iron; FeAsS; Fe = 34·3, As = 46·0, S = 19·7. Orthorhombic, holosymmetric.

$$a : b : c = 0{\cdot}677 : 1 : 1{\cdot}188.$$
$$m = \{110\}, \; e = \{014\}, \; l = \{011\}.$$
$$mm\ (110) : (1\bar{1}0) = 68^\circ\ 13', \; ll\ (011) : (0\bar{1}1) = 99^\circ\ 50'.$$

Twinned on (101) (Fig. 460). Cleavage {110}, fair. Brittle. Fracture, uneven. H = 5½; G = 6·0. Silver-white. Streak, grayish-black. Lustre, metallic. Opaque. Fusible to a magnetic bead. Decomposed by nitric acid.

With the above description compare crystals from **Lostwithiel** (Cornwall).

Mispickel, arsenical pyrites or arseno-pyrite (*Germ.* Arsenkies), is a fairly common mineral in various metalliferous veins, especially in those which yield tin, and it has been found well crystallised in several of the Cornish mines.

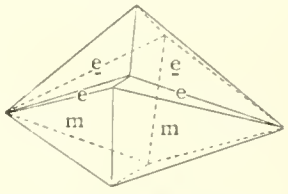

Fig. 460.—Mispickel, *m* {110}, *e* {014}, twinned on (101).

Like marcasite it is generally twinned, and some of the groups closely resemble those of marcasite. With the positions adopted above, both minerals twin according to two laws, namely, on {110} and on {101}, but the former is the more common mode of twinning in marcasite and the latter in mispickel; mispickel affords, like aragonite, an instance of twinning upon a pseudo-hexagonal prism; the angle of the macroprism {101} being 59° 22′. In marcasite the corresponding angle is 63° 40′. This large difference in the angles of the two minerals (and therefore in their axes) has raised some doubt as to whether they are to be regarded as isomorphous.

Some mispickel contains a considerable quantity (up to 9 per cent) of cobalt, due no doubt to isomorphous intermixture with the corresponding arseno-sulphide of cobalt, known as **glaucodote**; this is of course easily detected in the borax bead.

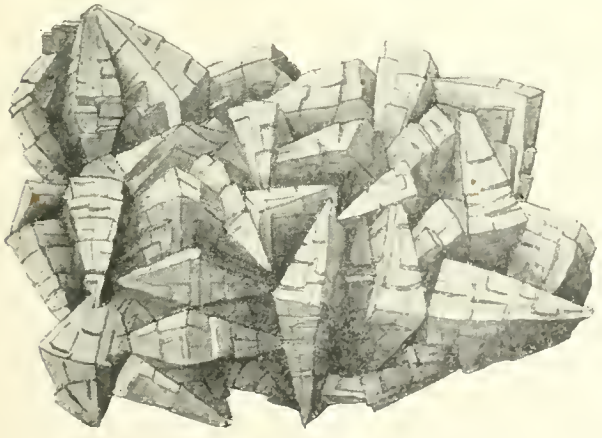
Fig. 461.—Mispickel from Tavistock (Devonshire); (Brit. Mus.).

Mispickel is a common ore of arsenic, and is largely worked as such in Cornwall. The best crystals of Cornish mispickel occur in a chlorite schist associated with cassiterite. The name mispickel is an old German mining term of unknown derivation.

The curious cruciform cavities filled with red earthy hydrate of iron found in slate at Clonmel in Ireland illustrate both the decomposition and the twinning of mispickel. They were called crucite or crucilite, and were supposed to be altered staurolite or some unknown mineral on account of their remarkable

form, crosses or stars with their arms meeting at angles of about 60° : there is no reason to suppose them anything else but mispickel prisms twinned on (101) which have been entirely decomposed.

SURVEY OF THE DISULPHIDES

The disulphides and arseno-sulphides constitute the following very complete and instructive isodimorphous series :—

Cubic.		Orthorhombic.	
Pyrites Group.	Cobaltite Group.	Marcasite Group.	Mispickel Group.
Pyrites FeS_2		Marcasite FeS_2 Löllingite $FeAs_2$	Mispickel FeAsS
Smaltite $CoAs_2$	Cobaltite CoAsS	Safflorite $CoAs_2$	Glaucodote (Fe,Co)AsS
Chloanthite $NiAs_2$	Gersdorffite NiAsS	Rammelsbergite $NiAs_2$	Wolfachite NiAsS
	Ullmannite NiSbS		
Hauerite MnS_2 Sperrylite $PtAs_2$			

All the cubic members of the above series appear to be pyritohedral except **ullmannite**; this mineral occurs in Sardinia as cubes striated like pyrites, but in Carinthia as tetrahedra; it must therefore really belong to the tesseral polar class (p. 51). We have seen above that there is some reason to think that pyrites also possesses this symmetry; it is therefore possible that the whole cubic series may belong to the ullmannite class.

Hauerite is found in fine isolated octahedral crystals in clay at Kalinka in Hungary, and at Raddusa in Sicily. **Sperrylite**, the only natural compound of platinum, occurs as brilliant microscopic crystals (pyritohedral combinations) in a nickeliferous ore consisting of various sulphides, at Sudbury in Ontario. Another member of the group is very rare, **laurite**, RuS_2, found in minute crystals in the platinum sands in Borneo.

The minerals grouped together under the name **gersdorffite** are mostly massive nickel ores containing a considerable quantity of iron and some cobalt; it seems almost necessary to regard them as mixtures in varying proportions of NiS, NiAs, NiS_2, and $NiAs_2$. Rammelsberg regarded them as mixtures of NiS_2 with Ni_mAs_n; the arsenides and antimonides of iron, nickel, and cobalt being, in his opinion, isomorphous mixtures or alloys of these elements.

It is remarkable that there is another arsenide of cobalt of quite different composition, $CoAs_3$, known as **skutterudite**, which is also cubic and pyritohedral.

SECTION V

THE SESQUI-SULPHIDES

THE STIBNITE GROUP

Stibnite.—Sulphide of antimony; Sb_2S_3; Sb = 71·8, S = 28·2. Orthorhombic. Common form, prism {110} terminated by {111}.

$$a : b : c = 0{\cdot}993 : 1 : 1{\cdot}018.$$

$$m = \{110\},\ B = \{010\},\ p = \{111\}.$$

$$Bm\ (010) : (110) = 45^\circ\ 13',\ pm\ (111) : (110) = 34^\circ\ 51',$$

$$Bp\ (010) : (111) = 54^\circ\ 36'.$$

Cleavage {010}, perfect. Glide-plane, (001). Slightly pliable. Fracture, conchoidal. H = 2; G = 4·6. Steel-gray. Streak, lead-gray. Lustre, metallic. Opaque. Easily fusible (1). Volatilises. Decomposed by HCl.

With the above description compare crystals from **Felsöbanya** (Hungary).

Stibnite or antimonite (*Germ.* Antimonglanz) is the only important ore of antimony, and is found massive in considerable quantities; the best crystallised specimens are those from the antimony mines of Ichinokawa in the island of Shikoku, Japan, where it occurs, as at other localities, in long striated prisms, but of a great size (more than a foot in length) and extraordinarily rich in many brilliant pyramid faces. At other localities the crystals are terminated by *p*, and only a few other pyramids, such as {113} {121}. The mineral can generally be recognised, even in massive specimens, by its perfect longitudinal cleavage and by horizontal lines and nicks on the cleavage surface which indicate a glide-plane parallel to the base {001}; for this reason also the crystals can be bent, and are often found curved and warped. Very remarkable are the twisted crystals found in Japan, and in some other places (Fig. 462); there is no evidence that these can be explained by vicinal twinning like twisted quartz (p. 375), neither has stibnite a right and left-handed character like quartz.

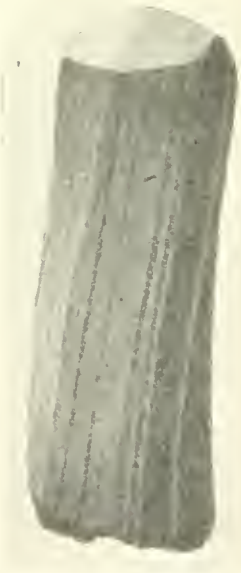

Fig. 462.—Stibnite, twisted crystal (Oxf. Mus.).

A cleavage surface of stibnite is excellently adapted to show that

heat is unequally conducted in different directions in a crystal. The experiment may be made in two ways :—

(1) *Senarmont's method.*—The face having been coated with a thin film of wax is touched with the point of a heated wire. The wax is melted round the wire, and the melted portion has the form, not of a circle, but of an ellipse, since heat is conducted more readily along the vertical axis *c* than along the horizontal axis *a*.

(2) *Röntgen's method.*—The face is breathed upon and then quickly touched with a heated wire. The thin film of moisture is driven away round the point of contact owing to the heat conducted by the crystal; and by rapidly dusting the surface with fine lycopodium powder, which adheres to the moist part, and can be shaken from the dry space, the latter is shown as before to have the form of an ellipse, whose major axis coincides with the vertical axis *c* and the minor axis with the brachy-diagonal *a*. This is in accordance with orthorhombic symmetry. In a cleavage plate of gypsum, on the contrary, the ellipse is obliquely situated, since in this mineral the plate is not perpendicular to the plane of symmetry.

Massive specimens often have a fibrous structure; the softness and fusibility of stibnite also serve to distinguish it from other sulphides containing antimony. It loses its brilliancy when exposed to the light and becomes black. The dark powder of stibnite was used in ancient times to darken the eyebrows, etc.

Stibnite is usually accompanied by white and yellow oxides of antimony resulting from its decomposition.

Some Noteworthy Localities :

Felsöbanya (Hungary).—Fine terminated crystals of stibnite occur in metalliferous quartz veins in trachyte, and are associated with barytes, blende, realgar, calcite, and quartz; the stibnite sometimes penetrates the tabular crystals of barytes (Fig. 660, p. 522); it is partly coated with yellow crusts of blende or with chalcedony.

Japan.—From the antimony mines of the island of Shikoku have come the finest specimens of stibnite: large prisms terminated by numerous lustrous faces. A huge group in the British Museum is one of the most striking mineral specimens in that collection; these crystals are sometimes as much as 18 inches long; they are frequently bent at the end.

The stibnite group includes **bismuthite**, Bi_2S_3, a comparatively rare mineral, and one which is not found in terminated crystals. The striated prisms of bismuthite are usually acicular; they possess the same cleavage as stibnite, and a similar prism angle, but only one crystal from Bolivia has yielded a macroprism {101} from which the vertical axis can be calculated. Artificial crystals also present only the prism zone.

The corresponding sulphide of arsenic, **orpiment** (*Germ.* Auripig-

ment, Operment), is not often found crystallised; small crystals can be extracted from clay at Tajowa in Hungary; these possess the same cleavage and glide planes as stibnite, but the angles are very different, so that there is some doubt whether orpiment is really isomorphous with stibnite and bismuthite.

As_2S_3	$a : b : c = 0{\cdot}603 : 1 : 0{\cdot}674$	prism angle 79° 20′.
Sb_2S_3	$a : b : c = 0{\cdot}993 : 1 : 1{\cdot}018$	,, 89° 34′.
Bi_2S_3	$a : b : c = 0{\cdot}968 : 1 : 0{\cdot}985$	,, 88° 8′.

Bismuthite is an opaque tin-white mineral of metallic lustre like stibnite; crystallised orpiment is a soft lemon-yellow translucent mineral of resinous lustre (pearly on the cleavage surface); the streak is bright yellow; the mineral is often found foliated or earthy as a decomposition product of realgar. **Realgar**, AsS, is found in fine translucent red monoclinic crystals in metalliferous veins in Hungary and other places; also as beautiful little crystals with blende and pyrites in the dolomite of the Binnenthal (see p. 320). It very readily changes to yellow orpiment when exposed to the action of light.

SECTION VI

THE SULPHO-FERRITES

CHALCOPYRITE

Chalcopyrite.—Sulpho-ferrite of copper; $CuFeS_2$; Cu = 34·5, Fe = 30·5, S = 35·0. Tetragonal; symmetry, ditetragonal alternating.

$$a : c = 1 : 0{\cdot}985.$$

$$p = o = \{111\},\ p' = \omega = \{\bar{1}11\},\ e = \{101\},\ C = \{001\},\ z = \{201\},$$
$$d = \{114\},\ u = \{44\bar{1}\}.$$

$$Ce\ (001) : (101) = 44^\circ\ 34',\ Co\ (001) : (111) = 54^\circ\ 20',$$
$$o\omega\ (111) : (\bar{1}11) = 70^\circ\ 7'.$$

Twinned about normal of (111) or on plane (101). Cleavage {201}, imperfect. Somewhat brittle. Fracture, conchoidal. H = 4; G = 4·2. Brass-yellow. Streak, greenish-black. Lustre, metallic. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystals from **French Creek** (Pennsylvania).

Chalcopyrite, copper pyrites, or towanite (*Germ.* Kupferkies, *Fr.* Cuivre jaune), is one of the commonest ores of copper, and the mineral from which most of the copper of commerce is derived; it is a common constituent of metalliferous veins, where it sometimes occurs in beautiful crystals, rivalling those of iron pyrites in perfection and lustre.

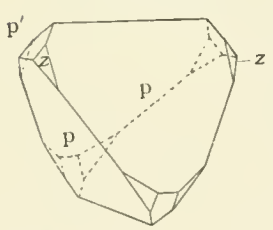

Fig. 463.—Chalcopyrite. p {111}, p' {$\bar{1}$11}, z {201}.

The angles of this mineral are very nearly those of the cubic system, and its axes are consequently very nearly equal. The crystals are commonly bisphenoids which resemble regular tetrahedra, or are apparent octahedra which really consist of two such complementary tetrahedra; the octahedron angle is then 70° 7′ (instead of 70° 32′). The mineral was in fact supposed to be cubic until in 1822 this small difference was established by accurate measurements. The true symmetry can sometimes be made out by careful examination of certain crystals which appear at first sight to be combinations of tetrahedron and cube; it will sometimes be found that of the six tetrahedron edges only four are

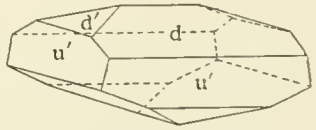

Fig. 464.—Chalcopyrite, d {114}, d' {$\bar{1}$14}, u' {44$\bar{1}$}.

truncated, and this is sufficient to show that the truncating faces belong to a square prism (Fig. 117) and not to a cube. In other cases the basal pinakoid may be present without this square prism (Fig. 127). The edges of the octahedral crystals are truncated by the form e {101}, and the corners are often replaced by z {201}; the basal pinakoid is rare.

The habit of the crystals varies much according to the bisphenoids present, which may either be acute (Fig. 463) or obtuse (Fig. 464).

The faces usually have a platy structure, and are much striated. The true symmetry of the mineral is clearly displayed by the striations and superficial characters of the "octahedron" faces. The faces of one "tetrahedron" o are bright, those of the complementary tetrahedron ω are dull, and are also more liable to oxidation. These differences are especially important in the interpretation of the twins, which are generally one or other of two kinds.

(1) Twin axis the normal to o (111), composition plane (111). These are twins of the spinel type, in which, as in blende (see Fig. 445, p. 318), bright faces of o meet dull faces of ω at the twin junction; they must therefore be described as due to hemitropy about the normal of o, and not to reflection over the plane of composition.

Composite twins (Fig. 465), found at Neudorf in the Harz, consist of five individuals, a central crystal to which four other crystals are symmetrically united by twinning on the four normals to the form {111}.

It will be noticed that the form z {201} is not a bisphenoid like o, but is a bipyramid.

(2) Twin plane e (101), composition plane (101). Here o is opposed to o, and ω to ω, across the twin junction; the doublet is symmetrical

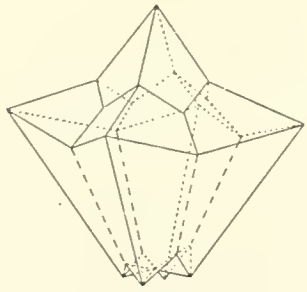

Fig. 465.—Chalcopyrite {201}, twinned on {111}.

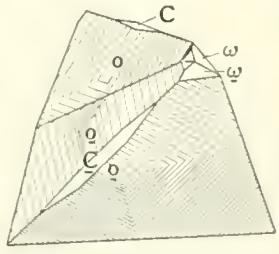

Fig. 466.—Chalcopyrite, o {111}, ω {$\bar{1}\bar{1}\bar{1}$}, C {001}, twinned on (101).

to the composition plane, and can only be described as due to reflection over that plane, and not to hemitropy about any edge of the crystal.

Fig. 466 represents the crystal on which the nature of this twin growth was first decisively established by Fletcher.

Like other compounds of sulphur and iron, chalcopyrite is readily liable to tarnish and surface alteration. Beautifully iridescent tarnished masses, common in Cornwall and elsewhere, are known as "peacock copper"; the prevalent blue colour of this tarnish may be due partly to the conversion of the chalcopyrite into covellite, CuS.

A curious massive variety is that found in some Cornish mines, and known as "blistered copper ore"; this is botryoidal or reniform, with a smooth, brassy surface.

Chalcopyrite is distinguished from iron pyrites by its softness, being easily scratched by the knife; also by yielding on treatment with nitric acid a green solution, which becomes blue on addition of ammonia; it can scarcely be mistaken for the sectile gold.

The variations in the composition of chalcopyrite are probably to be explained by the mechanical intermixture of iron pyrites. Thus two analyses of a single specimen from Freiberg gave the following:—

	Cu.	Fe.	S.	Formula.
I.	25·78	35·16	37·52	$2CuFeS_2 + FeS_2$
II.	30·66	34·11	35·23	$4CuFeS_2 + FeS_2$

Considerable doubt attaches to the constitutional formula of chalcopyrite; its liability to conversion into copper-glance Cu_2S induces some authors to regard it as best expressed by $Cu_2S \cdot Fe_2S_3$.

At Joplin in Jasper County, Missouri, chalcopyrite occurs in "tetrahedra" disposed in parallel positions upon blende; and the iridescent drusy crust which covers the tetrahedrite from Herodsfoot mine, near Liskeard, consists of tarnished chalcopyrite.

Like iron pyrites, chalcopyrite occurs in many and various surroundings, and is found massive in very large deposits often mixed with iron pyrites, pyrrhotite, and also with nickel sulphides. In many places auriferous chalcopyrite is worked as an ore of gold.

Some Noteworthy Localities:

St. Agnes (Cornwall).—The mineral was called towanite, after the Towan mine at this locality, where it occurred in large crystals of scalenohedral habit in metalliferous veins associated with quartz, chalybite, blende, cassiterite, and chlorite (Fig. 467).

Fig. 467.—Chalcopyrite with Quartz, from St. Agnes (Brit. Mus.)

French Creek (Pennsylvania).—Very perfect isolated sphenoidal crystals have been found in chlorite at the French Creek iron mines; these are acute bisphenoids {332}, like Fig. 126, p. 56.

Of the other compounds of copper, iron, and sulphur which may with chalcopyrite be classed together under the name sulpho-ferrites, one only is sufficiently common to be mentioned here.

Erubescite.—Sulpho-ferrite of copper; Cu_3FeS_3; Cu = 55·5, Fe = 16·4, S = 28·1. Cubic. Common form, cubes. Twinned on (111). Cleavage {111}, imperfect. Slightly sectile. Fracture, sub-conchoidal. H = 3; G = 5·0. Pinchbeck-brown. Streak, grayish-black. Lustre, metallic. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystals from **Carn Brea** (Cornwall).

Erubescite, bornite, variegated copper ore (*Germ.* Buntkupfererz, *Fr.* Cuivre panaché), occurs in irregular interpenetrating cubes twinned on (111); but more usually massive; very characteristic is the coppery and bronzy colour of this mineral even on a freshly fractured surface, and the vivid bluish tarnish which it assumes on exposure (hence the miners' name, "Horseflesh ore"). These superficial characters are sufficient to distinguish erubescite from argentite, and the sectility from other sulphides. The composition of the crystals is accurately represented by the formula given above, but massive specimens vary considerably, the percentage of copper ranging from 55 to 70; this may, however, be due to intermixture of copper-glance.

Pyrrhotite.—Sulphide of iron; Fe = 56 – 61; S = 44 – 39. Hexagonal or pseudo-hexagonal. Common form, hexagonal plates. Cleavage {110}, imperfect. Brittle. Fracture, uneven. H = 4; G = 4·6. Bronze-yellow. Streak, grayish-black. Lustre, metallic. Opaque. Magnetic. Fusible. Decomposed by nitric acid.

With the above description compare crystals from **Kongsberg** (Norway).

Pyrrhotite.—Magnetic pyrites (*Germ.* Magnetkies, Leberkies).—This mineral is of somewhat doubtful composition, and has sometimes been regarded as a compound in which iron enters into the acid radicle. The analyses indicate considerable variation. Different formulæ, ranging from Fe_6S_7 to $Fe_{11}S_{12}$, have been assigned to pyrrhotite; but they are all of the type Fe_nS_{n+1}. Some of the purest specimens approach very closely to the monosulphide FeS in chemical composition.

In the absence of optical measurements it is impossible to say for certain whether pyrrhotite is hexagonal or orthorhombic (pseudo-hexagonal). If hexagonal, it is perhaps to be classed with wurtzite and greenockite; the latter has for one of its pyramid angles 56° 6′, while that of pyrrhotite is about 53°; the etching figures on the basal plane, the prism cleavages, and the curve of thermal conductivity all point to hexagonal symmetry.

Pyrrhotite is usually massive with a tendency to laminar structure; but large crystals, thick hexagonal plates more than an inch in diameter, from Morrho Velho in Brazil, are preserved in the British Museum. Good but small crystals have been found at Kongsberg in Norway, and at Andreasberg in the Harz.

The peculiar bronzy colour of pyrrhotite, inclining to pinchbeck-brown, combined with its magnetic character, serve to distinguish it from iron or copper pyrites, and from other sulphides which may resemble it when they are slightly tarnished.

SECTION VII

THE SULPHANTIMONITES, ETC.

THE TETRAHEDRITE GROUP

Tetrahedrite. — Sulphantimonite of copper; Cu_3SbS_3; Cu = 46·8, Sb = 29·6, S = 23·6. Cubic; symmetry, ditesseral polar. Common form, tetrahedra.

$$o = \{111\},\ \omega = \{11\bar{1}\},\ d = \{110\},\ n = \{211\}.$$

Twin axis the normal to *o*. Brittle. Fracture, sub-conchoidal. $H = 3\frac{1}{2}$; G = 4·7. Lead-gray. Streak, dark brown. Lustre, metallic. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystals from **Kapnik** (Hungary).

Tetrahedrite, fahl-ore, or gray copper (*Germ.* Antimonfahlerz, *Fr.* Cuivre gris, Panabase), is a common ore of copper, and was taken above (p. 47) as the representative of ditesseral polar symmetry. The crystals are almost invariably of tetrahedral habit; the tetrahedra often have their edges bevelled by {211} (Fig. 468), and their corners replaced by the dodecahedron which constitutes a little three-faced pyramid upon each tetrahedron corner (Fig. 469). When the complementary tetrahedron $\omega\{111\}$ occurs, its faces are usually dull (specimens from Kapnik), or pitted with triangular markings (specimens from Dillenburg), and so may be distinguished from the tetrahedron $o\{111\}$. Where only one tetrahedron is present, it is apparently the latter. Sadebeck attempted to distinguish them by means of the other forms by which they are accompanied. He established the fact that when both the complementary forms {211} and $\{2\bar{1}1\}$ occur on the same crystal, the former is striated perpendicular to the dodecahedron edge which it truncates, while the latter is striated parallel to the dodecahedron edge which it truncates. Hence these forms serve to determine the tetrahedron which they accompany. Tetrahedrite is sometimes twinned on (111), one crystal having the edges and corners of smaller individuals projecting from its faces; the positions of the latter are derived by hemitropy about an axis joining a

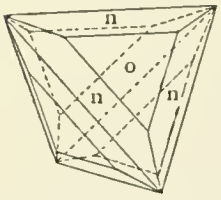

Fig. 468.—Tetrahedrite, *o* {111}, *n* {211}.

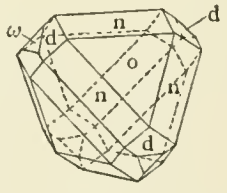

Fig. 469.—Tetrahedrite, *o* {111}, *n* {211}, *d* {110}, ω $\{11\bar{1}\}$.

corner of the tetrahedron to the centre of the opposite face, *i.e.* about a normal to (111), Fig. 470. It is noteworthy that supplementary twinning, like that of diamond, in which two individuals interpenetrate with their edges at right angles to each other (Fig. 421, p. 292) is almost unknown in tetrahedrite.

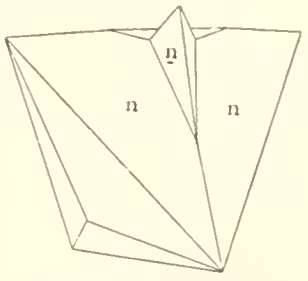

Fig. 470.—Tetrahedrite, $n\{211\}$, twinned about normal of (111).

The appearance and characters of tetrahedrite vary considerably with the elements which it contains, such as As, Fe, Zn, Ag, Hg; we shall therefore consider this mineral and those which are isomorphous with it, together, as one group: the two chief members being:—

Tetrahedrite, Cu_3SbS_3
Tennantite, Cu_3AsS_3

The old German mining term "Fahlerz" included both the sulphantimonite, tetrahedrite, and the corresponding sulpharsenite, tennantite (*Germ.* arsenfahlerz), with their isomorphous mixtures. Tennantite rarely contains other metals than copper and iron, but tetrahedrite and those fahl-ores which contain both antimony and arsenic vary widely in composition, owing to the partial replacement of the copper in the above formula by iron, silver, zinc, or mercury; in both minerals, but especially in tennantite, bismuth may partially replace the antimony and arsenic respectively. Many analyses may be reduced to the type $3R'_2S \cdot X_2S_3$ where R = Cu, Ag, Hg, and X = Sb, As, Bi, but they indicate also a small proportion of iron and zinc, probably present as the compound $6R''S \cdot X_2S_3$.

The following analyses illustrate the great range of variation in the composition of fahlerz:—

	S.	Sb.	As.	Cu.	Fe.	Zn.	Ag.	Hg.
Cornwall	23·95	23·97	...	44·08	2·17	3·64	1·31	...
Clausthal	24·10	26·80	...	35·70	4·50	0·90	8·90	...
Kapnik	25·31	24·21	2·88	37·83	0·94	7·25	1·32	...
Schwatz	22·96	21·35	...	34·57	2·24	1·34	...	15·57
Cornwall	26·61	...	19·03	51·62	1·95	...	...	...

The last of these is nearly pure tennantite. Freibergite is a name applied to the argentiferous varieties; that from Freiberg may contain as much as 30 per cent of silver (it is also called Weissgültigerz). The fahlerz from Schwatz in the Tyrol, which contains 16 per cent of mercury, is sometimes called schwatzite. Freibergite is lighter in colour than tetrahedrite; its streak is often reddish; schwatzite occurs in black drusy crystals characterised by a *dodecahedral* habit (Fig. 471), the predominant faces being those of the dodecahedron, while the tetrahedron faces are quite small.

Tennantite itself differs from tetrahedrite in being usually cubic or else dodecahedral in habit; it is also darker in colour.

The varieties of tennantite which contain zinc have been distinguished by the names "kupferblende" and "sandbergerite," and show a tendency to develop large faces of {211}, so that some crystals resemble Fig. 101, p. 48.

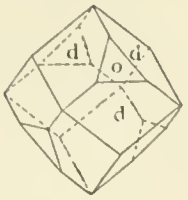

Fig. 471.—Tetrahedrite, d {110}, o {111}.

Fahlerz which contains lead has a slightly resinous lustre, but, whatever their differences in appearance, all the minerals and mixtures belonging to this group are recognisable, if crystallised, by their polar symmetry, metallic lustre, and absence of cleavage, combined with the reactions for copper, together with either antimony or arsenic.

Some Noteworthy Localities:

Binnenthal (Switzerland).—The most beautiful examples of tennantite, though small, are the brilliant crystals of cubic habit which occur with other metallic minerals in the white dolomite of the Binnenthal, described on p. 32 under blende. These were till lately supposed to be a distinct mineral and were known as "binnite."

Herodsfoot mine (Liskeard, Cornwall).—The tetrahedrite formerly found here is a vein-mineral on quartz veinstone, and occurs in large bevelled tetrahedra (Fig. 468), completely coated with brassy, or brilliantly tarnished, drusy chalcopyrite; on these specimens, crystals of quartz are often grouped into rectangular tables, possibly pseudomorphous after barytes, and the specimens may bear also galena and bournonite.

The minute crystals of copper pyrites which form a drusy coating on the Liskeard tetrahedrite are arranged in parallel positions, so that the principal axis of each crystal coincides in direction with one of the cubic axes of the tetrahedrite; they have probably resulted from the decomposition of the latter.

Kapnik (Hungary).—Sharply crystallised simple tetrahedra, and tetrahedra with edges bevelled by {211}, upon crystallised quartz of trigonal habit with brown blende and chalcopyrite; the vein stuff often contains pink rhodonite; a white clay usually occupies some of the corners between the quartz crystals.

Redruth (Cornwall).—Tennantite in gray dodecahedra, with cube and tetrahedron faces; the crystals are small and are associated with arsenic.

A table of the better established metallic compounds of sulphur with arsenic, antimony, and bismuth, will be found on p. 538; they are for the most part rare; in addition to fahlerz, the only members of the class which are to be found in almost all collections are stephanite, pyrargyrite and proustite, and bournonite.

STEPHANITE

Stephanite.—Sulphantimonite of silver; Ag_5SbS_4; Ag = 68·5, Sb = 15·2, S = 16·3. Orthorhombic; symmetry, polar.

$$a : b : c = 0{\cdot}629 : 1 : 0{\cdot}685.$$

B = {010}, d = {021}, p = {111}, z = {112}, m = {110}, A = {100}, C = {001}.

$Am\ (100):(110)=32^\circ\ 10'$, $Cd\ (001):(021)=53^\circ\ 52'$,
$pm\ (111):(110)=37^\circ\ 51'$.

Twinned on (110). Cleavage $\{010\}$, $\{021\}$, imperfect. Brittle. Fracture, conchoidal. $H=2\frac{1}{2}$; $G=6{\cdot}3$. Iron-black. Streak, black. Lustre, metallic. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystals from **Freiberg** (Saxony).

Stephanite. — Brittle silver ore (*Germ.* Schwarzgültigerz, Sprödglanzerz, Melanglanz, *Fr.* Psaturose). This mineral, which is important as an ore of silver, occurs in two habits, either as hexagonal prisms, or as flat hexagonal tables; in the latter, the prism faces may be absent or are very small; the crystals are almost invariably terminated by the smooth basal plane. Some of the crystals are very rich in pyramid faces. Twinning is constant and similar to that of aragonite, the mineral being pseudohexagonal; the crystals are usually traversed by twin lamellæ parallel to the prism $\{110\}$, and the twin junctions can be seen upon the basal plane. The polar character is only indicated by oblique striations upon the prism faces, similar to those of pyrargyrite (Fig. 472), which also show many apparently simple crystals to be supplementary twins like Fig. 232.

Though bright and lustrous when fresh, stephanite blackens like proustite on exposure to light. The best crystals occur at Freiberg, Saxony, both as prisms and as hexagonal plates with bevelled edges. Massive stephanite is worked on a large scale as an ore of silver in Nevada; stephanite and argentite being the chief ores of the famous Comstock Lode.

THE PYRARGYRITE GROUP

Pyrargyrite.—Sulphantimonite of silver; Ag_3SbS_3; $Ag=59{\cdot}8$, $Sb=22{\cdot}5$, $S=17{\cdot}7$. Hexagonal; symmetry, ditrigonal polar.

$a:c=1:0{\cdot}789$.

$a=\{10\bar{1}\}$, $e=\{110\}$, $r=\{100\}$, $t=\{310\}$, $v=\{20\bar{1}\}$, $u=\{2\bar{1}\bar{1}\}$, $d=\{\bar{4}23\}$.

$ee\ (110):(101)=42^\circ\ 5'$, $rr\ (100):(010)=71^\circ\ 22'$, $rv\ (20\bar{1}):(210)=35^\circ\ 12'$,
$rv\ (20\bar{1}):(\bar{1}02)=74^\circ\ 25'$.

Cleavage $\{100\}$, $\{110\}$, imperfect. Brittle. Fracture, conchoidal. $H=2\frac{1}{2}$; $G=5{\cdot}8$. Gray-black. Streak, purplish-red. Lustre, metallic-adamantine. Translucent. Refraction, strong, $\omega=3{\cdot}084$. Birefringence, negative, very strong; $\omega-\epsilon=0{\cdot}203$. Easily fusible. Decomposed by nitric acid.

With the above description compare crystals from **Andreasberg** (Harz).

Proustite.—Sulpharsenite of silver; Ag_3AsS_3; $Ag=65{\cdot}4$, $As=15{\cdot}2$, $S=19{\cdot}4$. Hexagonal; symmetry, ditrigonal polar (?).

$a:c=1:0{\cdot}804$.

$v=\{20\bar{1}\}$, $a=\{10\bar{1}\}$, $e=\{110\}$.

$ee\ (110):(101)=42^\circ\ 46'$, $rv\ (20\bar{1}):(2\bar{1}0)=35^\circ\ 18'$, $rr\ (20\bar{1}):(\bar{1}02)=74^\circ\ 39'$.

(See calcite, Figs. 526 and 528).

Cleavage $\{100\}$ imperfect. Brittle. Fracture, uneven to conchoidal. $H=2\frac{1}{2}$; $G=5{\cdot}6$. Scarlet-vermilion. Streak, scarlet. Lustre, adamantine.

Sub-transparent. Refraction, strong; $\omega = 2{\cdot}979$. Birefringence, negative, very strong; $\omega - \epsilon = 0{\cdot}268$. Easily fusible. Decomposed by nitric acid.

With the above description compare crystals from **Chañarçillo** (Chili).

This group, also known as the ruby silvers or red silver ores, includes **Pyrargyrite** (*Germ.* Antimonsilberblende, dunkles Rothgültigerz, *Fr.* Argyrythrose).

Proustite (*Germ.* Arsensilberblende, lichtes Rothgültigerz).

The red silvers afford an excellent example of isomorphism; their angles are nearly identical, and they occur in very perfect crystals of similar habit.

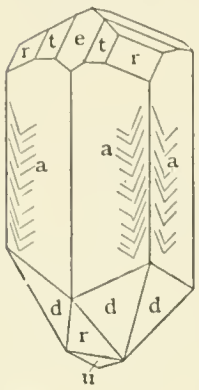

Fig. 472.—Pyrargyrite, *a* {101}, *r* {100}, *t* {301}, *e* {10$\bar{1}$}, *d* {42$\bar{3}$}, *r* {010}, *u* {$\bar{1}$21}.

Pyrargyrite is found mostly in prisms terminated by a low hexagonal pyramid {310} (Harz), or by the drusy basal plane (Mexico); proustite almost always in prisms terminated by the scalenohedron {201} with small faces of the flat rhombohedron {110}. The lustrous specimens of this habit from Chañarçillo are among the most beautiful examples known of mineral crystallisation. That in the British Museum is one of the treasures of the collection.

Both minerals twin according to several laws:

(1) Two prisms are juxtaposed at an angle of about 26°, the twin plane being (211).

(2) Two prisms are juxtaposed at an angle of about 86°; here the twin plane is (100); these rectangular twins are common in proustite, but rare in pyrargyrite.

(3) Two hemimorphic prisms of pyrargyrite are united so as to resemble a single crystal belonging to the calcite class; these may be described as twinned about the normal to (10$\bar{1}$); such twins are distinguished by the oblique striations on the prism faces of the two crystals.

Doubly terminated crystals are extremely rare, but the polar character of pyrargyrite is always indicated by these striations of the prism faces, which are not symmetrical towards both ends (Fig. 472).

According to the transparency of its surface pyrargyrite varies in colour; the darkest show a deep ruby gleam in thin splinters, but some specimens appear almost as light as proustite. Proustite has always the same ruby-red colour when fresh, but on exposure to light its surface becomes dead black, and specimens to be preserved must be kept covered. The two minerals may be safely distinguished by their streak.

Although the red silvers are obviously isomorphous, they rarely form mixtures; pyrargyrite generally contains some arsenic, but rarely as much as 3 per cent. The following analyses represent the greatest variations:—

	S.	Sb.	As.	Ag.
Pyrargyrite—				
Andreasberg	17·81	22·45	...	59·75
Chañarçillo	18·17	18·47	3·80	60·53
Proustite—				
Chañarçillo	19·52	...	15·03	65·10
Saxony	19·54	3·74	12·29	64·43

Two very rare minerals, **pyrostilpnite** and **xanthoconite**, seem to have the same composition as pyrargyrite and proustite respectively, and to belong to the monoclinic system, so that the group is to be regarded as isodimorphous.

The red silvers are distinguished by their colour and streak from other minerals. Proustite when massive resembles cuprite, but is distinguished by its relative softness, and by the reactions for silver.

Some Noteworthy Localities:

Andreasberg (Harz).—Pyrargyrite in grouped crystals in which the flat hexagonal pyramid {210} projects; sometimes smooth, bright faces of {110} truncate its edges, and {100} appears on the corners. Generally twinned on (211). As a vein-mineral with calcite, arsenic, and sometimes harmotome.

Chañarçillo (Chili). — Beautiful prisms of proustite with scalenohedral terminations; sometimes terminated by the apparent hexagonal pyramid *l*. These crystals are often coated by white asbestos, which can be stripped from the proustite and exposes the brilliant surface of the latter.

BOURNONITE

Bournonite.—Sulphantimonite of lead and copper; $PbCuSbS_3$; Pb = 42·5, Cu = 13, Sb = 24·7, S = 19·8. Orthorhombic.

$$a : b : c = 0{\cdot}938 : 1 : 0{\cdot}897.$$

$A = \{100\}$, $B = \{010\}$, $C = \{001\}$, $o = \{101\}$, $n = \{011\}$, $u = \{112\}$, $m = \{110\}$.
$Am\ (100) : (110) = 43^\circ\ 10'$, $Bn\ (010) : (011) = 48^\circ\ 7'$, $Co\ (001) : (101) = 43^\circ\ 43'$,
$Cu\ (001) : (112) = 33^\circ\ 15'$.

Twinned on (110). Cleavage {010}, very imperfect. Brittle. Fracture, conchoidal to uneven. $H = 2\frac{1}{2}$; G = 5·8. Lead-gray. Streak, gray-black. Lustre, metallic. Opaque. Fusible. Decomposed by nitric acid.

With the above description compare crystals from **Neudorf** (Harz).

Bournonite (*Germ.* Spiessglanzbleierz) occurs in very beautiful crystals; a series of splendent groups from Herodsfoot mine, near Liskeard, in Cornwall, is to be seen in the British Museum; and huge crystals from the Harz in the Berlin Museum. Bournonite was named after the mineralogist the Comte de Bournon. It is a mineral very rich in faces, generally tabular owing to the predominance of C, and having the edges and corners profusely modified. The prism faces are vertically striated, the others smooth. The crystals are chiefly interesting

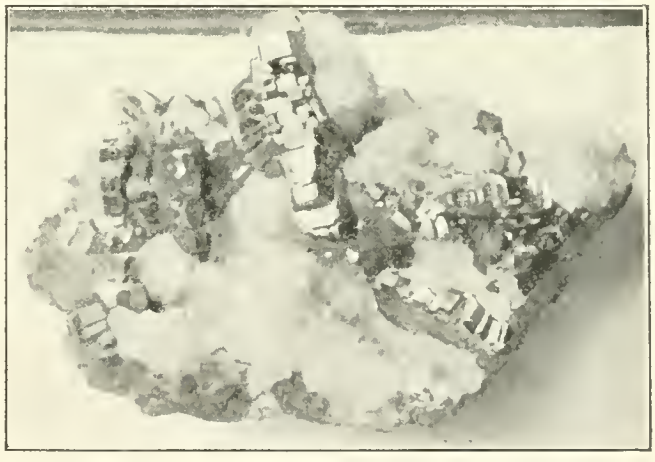

Fig 473.—Bournonite on Quartz, from Liskeard (Brit. Mus.).

on account of their twinning; each of the crystallographic axes may be called an axis of pseudo-symmetry, the angles of the prism, the brachydome and the macrodome being each nearly 90°, but twinning only takes place parallel to the faces of the prism of 86° 20′. Almost every crystal is a twin-group, or is traversed by a twin lamella parallel to the prism face; the twinning gives rise to cruciform and stellar plates, and even to groups resembling cog-wheels, which are known at Kapnik, in Hungary, by the name of "Rädelerz" (or wheel-ore). Even massive bournonite may be distinguished by the eye from other gray sulphantimonites, such as fahlerz, owing to the twin lamellæ, which can be discerned on a fractured surface. The composition is very constant, and the analyses do not generally indicate any isomorphous replacement of constituents, *e.g.*—

	S.	Sb.	Pb.	Cu.	As.	Fe.
Neudorf	19·63	25·68	41·38	12·68	...	...
Cornwall	20·30	26·30	40·80	12·70	...	...
,,	19·36	23·57	41·95	13·27	0·47	0·68

In the last of these a little As seems to replace Sb.

Some Noteworthy Localities:

Neudorf (Harz).—Tabular crystals with quartz, chalybite in brown rhombohedra {100}, and galena {111} with {311}, etc.

Herodsfoot Mine (Liskeard).—Twinned groups of short prisms united in wheel-shaped plates with uneven basal plane, but brilliant prism faces, on crystals of quartz. The re-entrant angles are formed by two faces of A {100}, and *o u* B *m n* are seen on the edges and corners (Fig. 473).

Kapnik (Hungary).—Rädelerz with quartz. The specimens often carry crystals of blende and tetrahedrite, together with pyrites and a little white clay. The bournonite is generally black, and only shows small faces of the domes and pyramids.

SURVEY OF THE SULPHANTIMONITES, ETC.

The sulphantimonites, sulpharsenites, and sulpho-bismuthites are commonly regarded as derived from sulpho-acids of the type $As(SH)_3$.

The normal sulpharsenites will then be represented by the formula $R''_3As_2S_6$ or $3R''S \cdot As_2S_3$; to these belong

Tetrahedrite	$3Cu_2S \cdot Sb_2S_3$	Cubic
Proustite	$3Ag_2S \cdot As_2S_3$	Hexagonal
Pyrargyrite	$3Ag_2S \cdot Sb_2S_3$	,,
Bournonite	$2PbS \cdot Cu_2S \cdot Sb_2S_3$	Orthorhombic

By some this group is regarded as dimorphous and analogous to the series of rhombohedral and orthorhombic carbonates $R''CO_3$, the corresponding angles being somewhat similar. But it may be questioned whether we are justified in looking upon $CaCO_3$ and Ag_3AsS as

similar compounds; moreover, aragonite twins on a prism of 63° 48′, whereas bournonite twins on a prism of 86° 20′.

Stephanite will be a salt of the acid $H_{10}Sb_2S_8$ or $5H_2S \cdot Sb_2S_3$, derived from the normal acid by the addition of two molecules of H_2S.

The number of the sulpharsenites, etc., is very considerable, although some of the minerals are rare; they must be referred to no less than eleven different sulpho-acids.

A particularly well-defined isomorphous series is that of the following orthorhombic minerals included under the formula $R''As_2S_4$:—

Wolfsbergite	$Cu_2Sb_2S_4$	or	$Cu_2S \cdot Sb_2S_3$
Emplectite	$Cu_2Bi_2S_4$	,,	$Cu_2S \cdot Bi_2S_3$
Scleroclase	$PbAs_2S_4$	,,	$PbS \cdot As_2S_3$
Zinckenite	$PbSb_2S_4$	,,	$PbS \cdot Sb_2S_3$

On the other hand, it is possible (with Tschermak) to regard such minerals as mixtures of various salts derived from such acids as $As'''(SH)_3$, $As'''S(SH)$, $As^{v}S(SH)_3$, in which arsenic is combined with both divalent S and monovalent (SH).

All the minerals of this class possess metallic lustre and most are gray in colour; the sulpharsenites are more translucent than the sulphantimonites and sulpho-bismuthites; those which contain lead have the most brilliant metallic lustre. These minerals are somewhat difficult to distinguish, since the optical characters cannot be utilised, but for this purpose the streak is useful, and they may all be determined by pyrognostic tests.

Other noteworthy compounds of sulphur are **jamesonite**, $Pb_2Sb_2S_5$, a fibrous or acicular mineral, which sometimes occurs in sufficiently large masses to serve as an ore of lead; **lorandite**, $TlAsS_2$, a rare mineral found in red crystals at Allchar, in Macedonia, almost the only prominent compound of thallium, of which element it contains no less than 59·4 per cent; **argyrodite**, Ag_8GeS_6, a drusy mineral, found in the Freiberg silver mines and subsequently in Bolivia, in which germanium was discovered by Winkler in 1886; **cylindrite**, the representative of a small but curious class of compounds containing tin together with lead, antimony and sulphur; it somewhat resembles graphite in appearance, and occurs in remarkable curvilaminar cylindrical forms in Bolivia, where several such sulpho-stannates containing silver are worked as ores of both tin and silver; another Bolivian mineral, **canfieldite**, $Ag_8(Sn,Ge)S_6$, a stanniferous argyrodite, is a link between these new and interesting minerals.

SECTION VIII

THE MONOXIDES

CUPRITE

Cuprite.—Oxide of copper; Cu_2O; Cu = 88·8, O = 11·2. Cubic; symmetry, tesseral holoaxial. Common form, octahedron.

$$A = \{100\},\ o = \{111\},\ d = \{110\}.$$

Cleavage, fair $\{111\}$, $\{100\}$. Brittle. Fracture, uneven. H = $3\frac{1}{2}$; G = 6. Cochineal-red. Streak, brownish-red. Lustre, metallic-adamantine. Translucent. Refraction very strong; $\mu = 2{\cdot}85$. Fusible. Soluble in strong hydrochloric acid.

With the above description compare crystals from **Liskeard** (Cornwall).

Cuprite (*Germ.* Rothkupfererz).—This mineral, which is also known by the names of red copper ore or ruby copper, is found beautifully crystallised in lustrous octahedra, cubes, and combinations of these forms with $\{110\}$ and $\{211\}$. The faces of the form $\{hkl\}$ are very rare, and since this is the only form which differs from the corresponding holosymmetric form, the holoaxial symmetry is only displayed in a few crystals. Some specimens from Wheal Phœnix, near Liskeard, bear faces of $\{8{\cdot}9{\cdot}6\}$ (Fig. 112), and others show faces of $\{13{\cdot}10{\cdot}12\}$. There is no other evidence of the true symmetry of the mineral, for etching figures appear to be holosymmetric, and the crystals do not rotate the plane of polarisation of plane-polarised light.

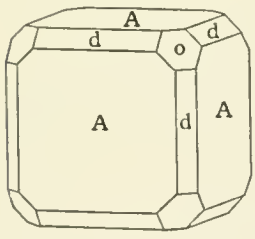

Fig. 474. — Cuprite, A $\{100\}$, d $\{110\}$, o $\{111\}$.

Twins of cuprite are unknown.

Massive cuprite somewhat resembles proustite in appearance, but is harder, and may be easily distinguished by the streak and blowpipe reactions. It occurs in sufficiently large quantities to be used as a profitable ore of copper.

Two curious varieties are the following:—

(1) Chalcotrichite, a beautiful capillary form in which the slender fibres resemble the finest hairs, and are crystals elongated either in the direction of a cube edge (a tetragonal axis) or of a cube diagonal (a trigonal axis). The most beautiful specimens of chalcotrichite hitherto

found are those from the old copper mines near **Gwennap** in Cornwall, and those recently found at **Morenci** in Arizona.

(2) Tile ore (*Germ.* Ziegelerz), an earthy variety of brick-red colour totally unlike the crystallised mineral in appearance; this is often very impure and much darkened in colour by intermixture with earthy hæmatite, limonite, and other minerals.

Some Noteworthy Localities:

Liskeard (Cornwall).—Brilliant cubic combinations situated on vein quartz whose cavities are lined with earthy limonite; the prominent faces are those of the cube and octahedron.

Gumeschevsk (Urals).—Crystals lining cavities in massive cuprite, which is often partially converted into malachite; the cuprite is either in octahedra, octahedra with truncated edges, or in combinations of cubic habit.

Chessy (near Lyons).—Large octahedra and dodecahedra, often with truncated edges and corners, completely altered on the surface to a smooth green crust of malachite. These crystals usually occur isolated in a soft white clay (lithomarge), and are, therefore, completely developed on all sides.

ZINCITE

Zincite.—Oxide of zinc; ZnO: Zn = 80·3, O = 19·7. Hexagonal; symmetry, dihexagonal polar. Cleavage, basal and prism $\{10\bar{1}0\}$, perfect. Brittle. Fracture, sub-conchoidal. H = 4 to 4½; G = 5·6. Blood-red. Streak, orange. Lustre, sub-adamantine. Translucent. Birefringence, positive. Infusible. Soluble in hydrochloric acid.

With the above description compare crystalline material from **Franklin Furnace** (New Jersey).

Zincite is found as a deep red massive mineral, with a platy structure, at the zinc mines of Sterling Hill, New Jersey, U.S.A., where it is a valuable ore of zinc. Zincite may be recognised by its orange yellow streak. Crystals are rare, and the form and symmetry were originally determined from the little white or yellow crystals of ZnO, which are occasionally formed by sublimation in the zinc-furnaces. Natural crystals have subsequently been found at Franklin Furnace, New Jersey, which have the same form (Fig. 475) as the artificial crystals.

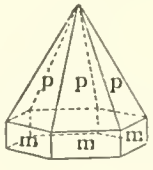

Fig. 475. — Zincite. *p* $\{10\bar{1}1\}$, *m* $\{10\bar{1}0\}$, *C* $\{000\bar{1}\}$.

Like wurtzite and greenockite, these are hexagonal (or dihexagonal ?) polar (compare the figures of greenockite on p. 76 and on p. 321). It is remarkable that these three substances, CdS, ZnS, and ZnO, possess not only the same symmetry but nearly the same angles, the angle $0001 : 10\bar{1}1$ between basal plane and pyramid is for greenockite 61° 54′, for wurtzite 62° 5′, for zincite 61° 54′. The first two are undoubtedly isomorphous in the ordinary sense, while zincite may be regarded as an

example of an oxide isomorphous, if the term may be so used, with the corresponding sulphide (and also with AgI), somewhat in the same way that $NaNO_3$ is "isomorphous" with $CaCO_3$.

MnO appears to enter into the composition of zincite as an isomorphous mixture, for some specimens contain as much as 7 per cent, and are then of a more yellow or orange colour, the uniformity of which, as described on p. 237, is evidence that the mixture is really a solid solution. From this it follows that MnO is probably dimorphous. Zincite occurs at Sterling Hill in black franklinite and pale green willemite, producing a rock which is a curiously mottled mixture of minerals. Pyrognostic tests generally give reactions for manganese.

Anhydrous monoxides, of which we have chosen cuprite as the representative, are rare in nature, and do not fall into well-defined isomorphous groups, or graduate into isomorphous mixtures. MgO (**periclase**), MnO (**manganosite**), and NiO (**bunsenite**) have been found in octahedra. **Water** (ice) is a hexagonal mineral. Another oxide of copper (**tenorite** or **melaconite**), CuO, is found at Vesuvius in black scaly crystals somewhat resembling mica, and belonging to the anorthic system.

HYDRATED MONOXIDES

Brucite.—Hydrate of magnesium; $MgO.H_2O$; $MgO = 69$, $H_2O = 31$. Hexagonal; calcite class. Cleavage, basal $\{111\}$, perfect. Sectile. Pliable. $H = 2\frac{1}{2}$; $G = 2{\cdot}4$. White. Streak, white. Lustre, waxy, pearly on (111). Translucent. $\omega = 1{\cdot}559$. Birefringence, positive, rather strong; $\epsilon - \omega = 0{\cdot}020$. Infusible. Soluble in hydrochloric acid.

With the above description compare crystals from **Texas** (Pennsylvania).

Brucite is generally found with magnesite and dolomite in serpentine as the result of the decomposition of magnesian silicates. It occurs in platy masses which somewhat resemble talc or gypsum in their softness, foliated structure, perfect cleavage and pearly lustre; it is, however, easily distinguished by the optical characters, gypsum being biaxial and talc having negative birefringence.

Some brucite is green or blue in colour.

SECTION IX

THE SESQUI-OXIDES

THE CORUNDUM GROUP

Corundum.—Oxide of aluminium; Al_2O_3; Al = 52·9, O = 47·1. Hexagonal; symmetry, dihexagonal alternating (calcite class).

$$a : c = 1 : 1{\cdot}363.$$

$$C = \{111\},\ R = \{100\},\ n = \{3\bar{1}1\},\ a = \{01\bar{1}\}.$$

$$RR\ (100) : (001) = 93^\circ\ 56'.$$

$$Rn\ (100) : (3\bar{1}1) = 25^\circ\ 59',\ CR\ (111) : (100) = 57^\circ\ 34'.$$

Parting (but not true cleavage) {111}, {100}. Brittle. Fracture, conchoidal. H = 9; G = 4. Blue. Streak, colourless. Lustre, vitreous. Transparent. Dichroic. Refraction, strong; $\omega = 1{\cdot}768$. Birefringence, negative, weak; $\omega - \epsilon = 0{\cdot}008$. Infusible. Insoluble in acids.

With the above description compare crystals of sapphire from **Ceylon.**

Corundum (*Germ.* Korund, *Fr.* Corindon) is well known in three of its varieties, ruby, sapphire, and emery.

Ruby and sapphire had attracted attention from the earliest times

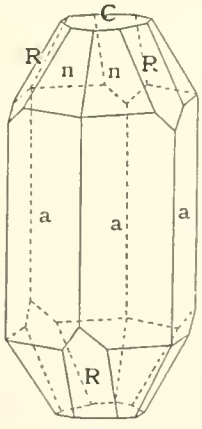

Fig. 476.—Corundum (sapphire). R {100}, *n* {3$\bar{1}$1}, C {111}, *a* {10$\bar{1}$}.

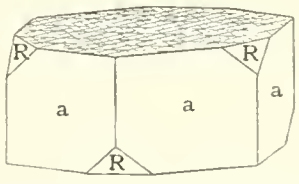

Fig 477.—Corundum (ruby), *a* {101}, R {100}, C {111}.

and were much prized as gemstones by the ancients, but Haüy was the first to refer them to the same species as the mineral which is now called corundum; this had been brought from China and was known as "adamantine spar" on account of its hardness. The latter substance

was analysed by Klaproth in 1787, and was supposed by him to contain a new earth in addition to alumina. Haüy was led to class these minerals together on account of the similarity of their cleavage.

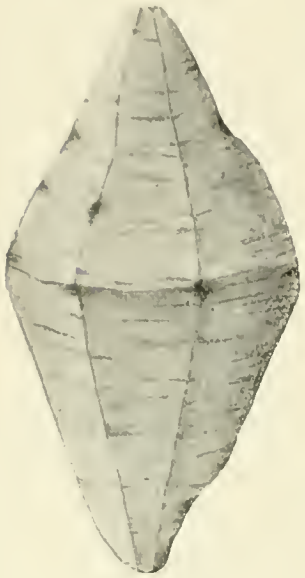

Fig 478.—Corundum from Ceylon.

Subsequently it was found that ruby, sapphire, and corundum consisted merely of alumina with a slight intermixture of silica and ferric oxide. Ruby and sapphire had previously been united by Haüy under the name "telesie" (or the perfect substance).

Corundum is rarely found well crystallised, but usually occurs as rolled and waterworn pebbles with other minerals in the gravel of river beds; owing to their hardness, however, some of these retain their crystalline form and even possess sharply-defined edges. The finest (blue) come from Ceylon; the best rubies come from Burma; good red crystals are also found in the dolomite of St. Gothard.

Few minerals possess a greater variety of colour than corundum; the common sorts are usually of a brown or reddish colour. Among those clear and transparent crystals which are suited for gemstones, the following are distinguished by special names:—

Ruby, red; Sapphire, deep blue to lilac; Oriental Topaz, yellow and brown; Oriental Emerald, green; Oriental Amethyst, purple. One variety is perfectly colourless.

The ordinary sapphire is barely translucent; the value of the transparent varieties depends upon their lustre and colour, and really fine pieces of good ruby of the peculiar colour known as "pigeon's blood" are even more highly prized than diamonds of the same weight.

The crystals of sapphire found in the gem-bearing sands and gravels are usually imperfect and more or less worn and rounded (Fig. 478); they are acute hexagonal bipyramids $\{13\bar{1}\}$ or $\{15\bar{3}\}$ (*cf.* p. 71), sometimes capped by $\{111\}$ with small faces of the rhombohedron $\{100\}$ upon alternate corners of the base. Crystals of ruby from Burma, and those from Montana, are tabular, owing to predominance of the basal pinakoid (Fig. 477). The base is almost always traversed by a triangular system of striations due to lamellar twinning on the rhombohedron R $\{100\}$ (twins of two distinct crystals juxtaposed according to this law like those of calcite are extremely rare); the parting or apparent cleavage parallel to R seems to be due to this lamellar twinning, which may perhaps be in many cases secondary, and caused by pressure, planes parallel to R then becoming glide-planes. The parting parallel to the basal plane appears to be due to incipient decomposition. Crystals of corundum often exhibit a pearly lustre on the base and a platy structure parallel to the same; these are due to microscopic cavities produced along horizontal planes $\{111\}$, which are therefore to be regarded as "solution planes," along which corrosion

takes place most easily. Somewhat similar is a third parting parallel to the hexagonal prism $\{10\bar{1}\}$.

Cleavage fragments of corundum resemble striated cubes and may be mistaken for a cubic mineral; but the hardness is always sufficient to distinguish corundum from all other minerals; it is scratched by diamond alone.

Remarkable are the so-called "asteriated" or star sapphires, which exhibit a six-rayed opalescent star when viewed nearly in the direction of the principal axis, a variety mentioned by Pliny. Such crystals are usually cut by jewellers with a curved surface (*en cabochon*) to display the effect. This "asterism" is due to minute tubular cavities arranged in planes parallel to the prism $\{10\bar{1}\}$, and caused by the same corrosion as the third parting just mentioned; it may be compared with the play of colours of orthoclase (moonstone), labradorite, and diallage.

Sometimes the corrosion cavities of corundum are filled with decomposition products, which give the crystals a bronzy submetallic lustre or sheen upon the basal plane.

Corundum is often, but not always, biaxial, the angle between the optic axes being small ($2V = 0° - 10°$); basal sections viewed between crossed nicols are seen to consist of six triangular sectors. Some authors, therefore, regard the crystals as triplets, and as really orthorhombic or even monoclinic; according to others the optical peculiarities may be explained as due to a laminar structure produced by secondary twinning on the planes R.

Corundum (even the clearest ruby or sapphire) generally contains a little ferric oxide, a little silica, and sometimes a trace of water, but otherwise consists simply of alumina. In the early analyses a considerable percentage of silica was found, but this may have been partly due to material abraded by the hard corundum from the agate mortar in which it was powdered.

The great differences in colour among the varieties of the gem-stone, which have led to its receiving the names oriental—amethyst,—topaz,—emerald, etc., are probably due to the ferric oxide, and perhaps also to traces of chromium. Its value as a gem is chiefly due to the colour, and to the high refractive power which, as in many minerals, accompanies great density and hardness. The dichroism is sufficiently characteristic to be used as a means of identification; in ruby the colours seen in the dichroscope are deep red (ω) and violet-red (ϵ); in sapphire the colours are deep blue (ω) and greenish or yellowish-blue (ϵ).

Emery (*Germ.* Smirgel) is the name applied to the dark granular varieties of corundum so largely used as a polishing material; they consist usually of an intimate mixture of blue corundum with magnetite and also hæmatite; this material was formerly brought almost exclusively from the Island of Naxos or some of the neighbouring islands in the Grecian Archipelago, where it is found in a crystalline limestone, associated with schist and gneiss; it is now found in many places. A better polishing material is the massive variety of pure corundum, such as the compact, purplish material formerly brought from Salem, Madras.

In many localities where it is found, corundum is accompanied by the aluminium hydrates, diaspore, gibbsite, and bauxite; it is sometimes converted into aluminous silicates, such as margarite and damourite. The best gemstones are found, as in Ceylon, in river gravels and sands, and not in their original matrix.

The artificial production of ruby has been a matter of great commercial interest; crystallised corundum has now been manufactured in a variety of ways, and the rubies made by Frémy's process, or by allied methods, have been, and are, actually used as gemstones. This method consists in the fusion of alumina, potassium carbonate, barium (or calcium) fluoride, and a little potassium chromate, the last being added in order to give a red colour to the crystals; the mixture is maintained at a temperature of 1500° C. for several days, when the corundum solidifies as tabular crystals of ruby, having on their edges faces of the rhombohedron R (Fig. 477).

Some Noteworthy Localities:

Burma.—At Mogok, in the neighbourhood of Mandalay, ruby occurs in a crystalline limestone, together with spinel, pyrrhotite, graphite, phlogopite, etc.

The crystals, rarely well developed, are a combination of basal pinakoid and rhombohedron like the artificial crystals; both the ruby and spinel are corroded, the former along the rhombohedron faces.

Campolongo, St. Gothard, Switzerland.—Opaque red or blue crystals, generally very imperfect, but sometimes in prisms terminated by pyramid faces, occur in the white dolomite. Associated with them are silvery mica, diaspore, and green tourmaline.

Thibet.—Large irregular pyramids, said to come from Thibet, are of a brown colour, and show a remarkable bronze lustre and hexagonal banding on the basal plane—both due to the corrosion described above.

Hæmatite.—Oxide of iron; Fe_2O_3; Fe = 70, O = 30. Hexagonal; symmetry, dihexagonal alternating (calcite class).

$$a : c = 1 : 1{\cdot}3656.$$

$r = \{100\}$, $C = \{111\}$, $n = \{3\bar{1}1\}$ $u = \{211\}$, $e = \{110\}$, $a = \{01\bar{1}\}$.

rr (100) : (010) = 94° 0′, rn (100) : $(3\bar{1}1)$ = 26° 0′.

Cleavage (parting), r, C, imperfect. Brittle. Fracture, uneven. H = 6; G = 5·2. Iron-black, blood-red when translucent. Streak, brownish-red. Lustre, metallic. Nearly opaque. Fusible with difficulty. Soluble in hydrochloric acid.

With the above description compare crystals from **Elba.**

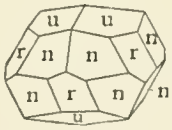

Fig. 479.—Hæmatite, n $\{3\bar{1}1\}$, u $\{211\}$, r $\{100\}$.

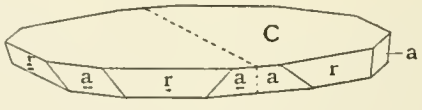

Fig. 480.—Hæmatite, twin, united along $(\bar{1}\bar{1}2)$.

Hæmatite, specular iron, micaceous iron ore, iron glance (*Germ.* Eisenglanz; *Fr.* Fer oligiste), a very important ore of iron, is isomor-

phous with corundum. The name hæmatite is as old as Theophrastus and Pliny, and denotes the blood-red colour of some of the ordinary massive varieties; but the mineral when crystallised is of a totally different appearance, and to this the names specular iron and iron glance refer. The crystals are often brilliant steely plates with modified edges, as shown in Fig. 480. But the finest crystals, those from the iron mines of the Island of Elba, are stout combinations of rhombohedra r, u, with the hexagonal bipyramid $n\{13\bar{1}\}$. A typical combination is shown in Fig. 479. In these the obtuse rhombohedron u may be recognised by its horizontal striations and convex surface.

The tabular crystals are more common in other localities; their tendency to form rosette-shaped groups (*Germ.* Eisenrosen) has been mentioned and illustrated on p. 249. Fig. 481 is from a photograph of a hæmatite rosette. Twin crystals are not rare among the crystals of rhombohedral habit in which two individuals interpenetrate by hemitropy about the principal axis or by reflection over $(2\bar{1}\bar{1})$; in the crystals of tabular habit, two plates overlap or interpenetrate, but sometimes the two individuals unite with plane of composition parallel to the prism $(2\bar{1}\bar{1})$ so as to form a single plate, as shown in Fig. 480. Fine lamellæ parallel to the rhombohedron r, as in corundum, indicate lamellar (possibly also secondary) twinning parallel to $\{100\}$; as in corundum, this twinning gives rise to a parting parallel to r, which must not be confused with a true cleavage. A further resemblance to corundum is supplied by a second parting parallel to the base C $\{111\}$, which is also due to a lamellar structure.

Hæmatite is one of the few minerals in which the electric conductivity has been accurately measured; it is found to be about twice as great in the vertical as in a horizontal direction.

In very thin flakes, such as can sometimes be found under the microscope, the mineral is seen to be really blood-red by transmitted light.

Very thin scaly varieties of hæmatite are red and quite soft, and adhere to the fingers like graphite when touched.

Common massive hæmatite, known by the name of red hæmatite, is brownish-red in colour, generally possesses a fibrous structure, which is cut transversely by a curvilaminar banding, and the surface is often botryoidal or reniform (*cf.* Fig. 404, p. 254). The botryoidal masses with radial-fibrous structure, common in Cumberland, break up into conical forms known there as "pencil-ore." Compact hæmatite has been used in ancient and modern times and in many parts of the world for ornamental purposes.

Earthy hæmatite, red ochre, or reddle, is a light-red earthy material generally mixed with clay.

Some iron ore, *e.g.* that of the Lake Superior region and of Cumberland, consists mainly of hæmatite.

In some of its modifications hæmatite may resemble limonite or some other hydrate of iron, but the red or reddish-brown streak serves to distinguish it from such minerals, whose streak is in general brown.

Some Noteworthy Localities:

Cumberland and **Lancashire.**—Specular iron ore occurs in the iron mines of Cleator Moor in splendent black plates, so grouped upon rock crystal as to present a velvety appearance; the plates have their edges formed by the rhombohedron *r*, and are sometimes slightly convex. The massive mineral from the same locality is the typical red hæmatite and pencil ore mentioned above; its surface is often transformed into black limonite; the best specimens are from Ulverstone. The iron ores here fill fissures and cavities in the carboniferous limestone.

St. Gothard (Switzerland).—Tabular crystals grouped into "Eisenrosen"; these are sometimes stout tables bounded by the hexagonal prism; they are associated with adularia, often twinned, as in Fig. 597 of orthoclase, p. 456, and with rock crystal or smoky quartz, muscovite, etc., lining cavities in gneiss and granite.

Fig. 481.—Hæmatite from St. Gothard.

Island of Elba.—The stout rhombohedral crystals of Fig. 479 occur under the conditions described on p. 328. The hæmatite is often brilliantly tarnished.

Vesuvius.—Small brilliant crystals of hæmatite line cavities in a trachytic lava, where they appear to have been formed by the action of vapours (perhaps ferric chloride); these crystals are usually platy and skeletal.

Hæmatite and corundum are clearly isomorphous, although in nature they scarcely enter into isomorphous mixture; and artificially prepared Ti_2O_3 and Cr_2O_3 are isomorphous with them. The former compound probably enters into the constitution of many hæmatites which are titaniferous; the rosette crystals of St. Gothard contain about 6 per cent of titanium. There is, however, also a mineral known as ilmenite (*Germ.* Titaneisen; *Fr.* Fer titané), containing from 30 to 40 per cent of TiO_2, which is often regarded as an isomorphous mixture of Fe_2O_3 and Ti_2O_3; ilmenite is slightly magnetic and occurs in platy crystals with triangular striations.

Ilmenite is found in well-defined crystals in the diorite of Krageroe in Norway, and at other localities, and crystallises in the hexagonal system with angles very near those of hæmatite, but with the hexagonal alternating symmetry of the dioptase class. It has been argued that in respect of this reduction of symmetry ilmenite, as compared with hæmatite, is analogous to dolomite, as compared with calcite.

Recently, however, the analysis of varieties which contain a considerable proportion of magnesia has indicated that some ilmenite conforms exactly to the formula $RO.TiO_2$, if R be used to denote Fe and Mg capable of replacing each other. The mineral should then be

regarded as a titanate of magnesium and iron, an isomorphous mixture of $MgTiO_3$ and $FeTiO_3$, and finds its place among the silicates and titanates, where it apparently belongs to the same isomorphous group with the mineral pyrophanite, $MnTiO_3$ (p. 434). Nevertheless these minerals certainly have angles nearly identical with those of hæmatite, and the "isomorphism" of the two groups may be compared with that of zincite and wurtzite, mentioned on p. 349.

THE HYDRATED SESQUI-OXIDES

Limonite.—Hydrate of iron; $2Fe_2O_3 . 3H_2O$; $Fe_2O_3 = 85{\cdot}5$, $H_2O = 14{\cdot}5$. Amorphous. Fracture, uneven to fibrous. $H = 5\frac{1}{2}$; $G = 3{\cdot}8$. Dark brown. Streak, yellowish-brown. Lustre, submetallic. Opaque. Fusible with difficulty to a magnetic bead. Soluble in hydrochloric acid.

With the above description compare botryoidal masses from **Lostwithiel** (Cornwall).

Göthite.—Hydrate of iron; $Fe_2O_3 . H_2O$; $Fe_2O_3 = 89{\cdot}9$, $H_2O = 10{\cdot}1$. Orthorhombic.

$$a : b : c = 0{\cdot}918 : 1 : 0{\cdot}607.$$
$$(110) : (1\bar{1}0) = 85^\circ\ 8'.$$

Cleavage {010}, perfect. Brittle. Fracture, uneven. $H = 5$; $G = 4{\cdot}2$. Blackish-brown. Translucent. Birefringence, positive. Axial plane (001). Acute bisectrix perpendicular to (010). $2E = 50^\circ$; $\rho < v$. Dichroic. Fusible with difficulty to a magnetic bead. Soluble in hydrochloric acid. Weakly magnetic.

With the above description compare crystals from **Lostwithiel** (Cornwall).

Manganite.—Hydrate of manganese; $Mn_2O_3 . H_2O$; $Mn_2O_3 = 89{\cdot}7$; $H_2O = 10{\cdot}3$. Orthorhombic.

$$a : b : c = 0{\cdot}844 : 1 : 0{\cdot}545.$$
$$(110) : (1\bar{1}0) = 80^\circ\ 20'.$$

Twinned on (011). Cleavage {010} perfect, {110} imperfect. Brittle. Fracture, uneven. $H = 4$; $G = 4{\cdot}4$. Steel-gray. Streak, reddish-black. Lustre, sub-metallic. Opaque. Infusible. Soluble in hydrochloric acid with evolution of chlorine.

With the above description compare crystals from **Ilfeld** (Harz).

Psilomelane.—Hydrate of manganese (barium, potassium, etc.). Amorphous. Fracture, smooth. $H = 5\frac{1}{2}$; $G = 4{\cdot}2$. Black. Streak, brownish-black. Lustre, submetallic. Opaque. Fusible with difficulty. Soluble in hydrochloric acid with evolution of chlorine.

With the above description compare botryoidal masses from **Lostwithiel** (Cornwall).

A number of hydrates of iron and of aluminium are mentioned in the table on p. 539.

Among these **limonite**, $2Fe_2O_3 . 3H_2O$, is the most common; it is a very frequent product of decomposition of other iron minerals and often occurs as a black amorphous crust upon their surface: it is frequently found as a "pseudomorph" after minerals containing iron. Brown or black crystals of iron pyrites, magnetite, or chalybite, preserving all their original sharpness of outline, sometimes consist entirely of limonite;

otherwise the mineral is stalactitic, botryoidal or earthy—never crystallised; it is often black and glazed on the surface, and from this character derives one of its names, "stilpnosiderite." The name limonite (λειμών, a meadow) really refers to "bog-iron ore," which is a brownish-yellow deposit common in marshes, and derived from the ferrous carbonate and sulphate dissolved in their waters; this often coats or replaces decaying vegetable matter; and it is well known as the iridescent slime common in marshy pools.

In **Sweden** the limonite forms large concretionary masses at the bottom of lakes (*Swed.* Sjömalm), and is worked as an ore of iron; when the concretions are small spherical nodules the ore is known as "pea-iron" (*Germ.* Bohnerz). Limonite can generally be recognised and distinguished from other hydrates of iron by its brownish-yellow streak and hardness of 5; but these amorphous and somewhat ill-defined hydrates pass into each other and frequently occur together as decomposition products of iron minerals.

The brown cellular quartz known in Cornwall as "gossan" (*Germ.* eiserner Hut, *Fr.* Chapeau de fer), which often constitutes the outcrop of metalliferous veins, and is regarded as an indication of their existence below the surface, contains earthy minerals consisting largely of ferric hydrates as decomposition products of iron pyrites; such hydrates, together with hæmatite, account for the prevalent red and yellow colour of most rocks and mineral specimens which contain iron compounds.

Among the ferric hydrates, **göthite**, FeO(OH), is conspicuous as a mineral which is found in lustrous black or brown orthorhombic prisms with pyramidal terminations; some of the finest specimens were found in the iron mines of Lostwithiel in Cornwall; it also occurs in fine red scales, bounded by {010} (lepidocrocite), constituting masses of velvety lustre; göthite in this form is one of the common alteration products which line secondary cavities in decomposing minerals, and sometimes give them a bronzy sheen or opalescence; the scales may be recognised under the microscope, and distinguished from hæmatite, by their dichroism, since the scales of the latter are basal pinakoids of a hexagonal mineral, and therefore not pleochroic.

The delicate radial groups of acicular crystals from Przibram in Bohemia have quite a silky appearance, and are known as "Sammetblende."

To the same group with göthite belong **diaspore**, AlO(OH), and **manganite**, MnO(OH). Diaspore is generally a white, cleavable, scaly, brittle mineral, of talcose appearance, which may be recognised as an alteration product of alumina, since it is generally found accompanying corundum and emery, and as a coating on crystals of corundum. It can be distinguished from gypsum, talc, and brucite by its superior hardness ($6\frac{1}{2}$); the cleavage flakes {010} are perpendicular to the third mean line, and the birefringence is strong. Manganite (*Fr.* Acerdèse) occurs in steel-gray crystals of sub-metallic lustre (H = 4), which are prisms with obtuse terminations, vertically striated, and frequently twinned; the specimens from Ilfeld, in the Harz, are very fine. When the crystals

are soft, this is due to their dehydration and partial conversion into the earthy oxide, pyrolusite, MnO_2.

Among other hydrates of manganese are **psilomelane**, a black *amorphous* mineral; it is usually botryoidal or stalactitic, and may be distinguished from most minerals of similar appearance by its superior hardness, which is greater than that of manganite; the streak distinguishes it from limonite. Psilomelane contains variable proportions of barium, potassium, and sodium, with from 3 to 6 per cent of water; its constitution is uncertain.

Among the aluminium hydrates, **bauxite**, $Al_2O_3 . 2H_2O$ (?), a white, brown or red, massive, concretionary, or earthy mineral, is of importance as one of the best ores of aluminium; the name is derived from Baux, near Arles, in France, where the mineral was first found.

SECTION X

THE DIOXIDES

THE CASSITERITE GROUP

Cassiterite. — Oxide of tin; SnO_2; Sn = 78·6, O = 21·4. Tetragonal; holosymmetric.

$$a : c = 1 : 0{\cdot}672.$$

$$s = \{111\},\ A = \{100\},\ m = \{110\},\ e = \{101\},\ h = \{210\},\ z = \{321\}.$$

$$ss\ (111) : (1\bar{1}1) = 58^\circ\ 19',\quad ms\ (110) : (111) = 46^\circ\ 27'.$$

Twinned on (101). Cleavage {110}, imperfect. Brittle. Fracture, subconchoidal. H = 6½; G = 7·0. Brown. Streak, gray. Lustre, adamantine. Translucent; $\omega = 1{\cdot}997$. Birefringence, positive, strong; $\epsilon - \omega = 0{\cdot}097$. Infusible. Insoluble in acids. With soda on charcoal, yields tin.

With the above description compare crystals from **St. Agnes** (Cornwall).

Cassiterite or tinstone (*Germ.* Zinnstein, *Fr.* Étain oxydé) is almost the only ore of tin, and is named from the Greek word for that metal;

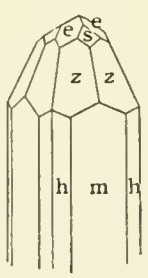

Fig. 482.—Cassiterite, *m* {110}, *h* {210} *s* {111}, *e* {101}, *z* {321}.

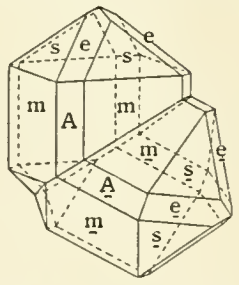

Fig. 483.—Cassiterite, *m* {110}, A {100}, *s* {111}, *e* {101}, twinned on (011).

good crystals are comparatively rare, but the density and hardness, and the adamantine lustre of the crystal faces, even when they are imperfect, serve to distinguish the mineral. Simple crystals are unusual; where they occur they may be of two types, either stout square prisms terminated by the faces *s*, *e* (Fig 483), or slender prisms terminated by acute pyramid faces (Fig. 482); the latter ("needle tin") are comparatively rare; in Cornwall, where very acute crystals of this type (with {321} and {521}) used to be found in the tin mines of the Camborne district, they were known as "sparable tin" from their resemblance to "sparable (sparrow bill ?) nails"; the apex of the pyramidal termination is only

very rarely truncated by the basal plane. Other prism faces occur, and this zone is vertically striated; the striations will help the student to identify the prism zone on twin crystals, which are very frequent and not easy to decipher; they are, as shown in Fig 483, of the first habit; the plane (101) of twinning and combination can generally be located by a re-entrant angle at the corner of the knee-shaped doublet; it is this corner which generally protrudes from the specimen.

Repetition of the twinning upon different faces of the form {101} is very common, and leads to a succession of these knee-shaped corners in which the two striated prism zones meet at angles of 67° 50′ (Fig. 484). Cassiterite usually contains Fe_2O_3, to which, as well as to other impurities (Ta_2O_5, etc.), its varying shades of colour are no doubt due; some cassiterite from the Malay peninsula is almost colourless, some from New England, in Australia, is a ruby red, some from Mexico is yellow; there are even specimens in the British Museum of transparent cassiterite facetted as a gem; the lustre and hardness would fit this mineral for a gemstone were it more often transparent. Most cassiterite is almost black. Among the massive varieties the so-called "wood tin" (*Germ.* Holzzinnerz) is remarkable as a dull mineral of wooden appearance, which possesses none of the adamantine lustre of the crystals; it is botryoidal, with a radiated fibrous structure, consisting of concentric curvilaminar layers, usually of different shades. "Toad's-eye tin" is a Cornish name for little brown-banded spherical nodules with the same radial fibrous structure.

Fig. 484.—Cassiterite, twin group (Oxford Museum).

Owing to its hardness, density, and resistance to solvents, cassiterite is one of the minerals which are not only mechanically concentrated by the action of running water, but remain unaltered in alluvial deposits in the form of pebbles or sand. This is commonly known as "stream tin"; it has been worked as an ore in Cornwall, where the finely divided cassiterite from old workings sometimes accompanies vegetable and animal remains; stream tin is worked on a large scale in the Malay peninsula and in Australia.

Specimens from the typical localities in all collections illustrate the peculiar associations of cassiterite; it is found lining cavities in gneiss and granite or rocks accompanying them, and is associated with apatite, zinnwaldite, topaz, tourmaline, and fluor, together with quartz, wolframite, axinite, scheelite, and beryl; the almost invariable presence of some of the five first mentioned fluorine minerals has led many (following Daubrée) to believe that the contents of these cavities and veins are due to the action of gaseous compounds of fluorine (and boron). In support

of this theory experiments made by Daubrée showed that cassiterite can be artificially produced by the action of steam on the vapour of chloride or fluoride of tin; moreover, the granite is sometimes altered into "greisen," a mixture of quartz and mica impregnated with topaz, cassiterite, tourmaline, and fluor.

Beautiful artificial crystals of cassiterite have recently been described, which are formed in the tin works by quite a different process, namely, the oxidation of metallic tin; these are of a violet colour and are not twinned, whereas twinning is almost universal in natural occurrences of the mineral.

There is, however, evidence that cassiterite may also have been deposited from solutions; it is found impregnating, and even replacing organic remains, and near Penzance a tin ore was formerly worked consisting of chlorite nodules cemented together by cassiterite.

Some Noteworthy Localities:

St. Agnes (Cornwall).—In the mines of this and other Cornish districts cassiterite occurs in quartzose lodes both in the granite and slate, near their junction; the veinstuff is a mixture of cassiterite and quartz, and the crystals, mostly of gray and brown colour, are generally the twins of Fig. 483, recognisable by the re-entrant angles.

Erzgebirge.—Beautiful specimens come from the tin mines on the northern (Saxon) and southern (Bohemian) sides of this range. At Zinnwald in Saxony and at Zinnwald and Schlaggenwald in Bohemia the cassiterite occurs near the contact of the granite with the slate, either as an impregnation in greisen, or in fine black twinned crystals in veins of the granite associated with zinnwaldite, topaz, apatite, quartz, fluor, and molybdenite. Portions of the greisen consist entirely of a granular mixture of cassiterite and topaz.

Rutile.—Oxide of titanium; TiO_2; Ti = 60, O = 40. Tetragonal; holosymmetric.

$$a : c = 1 : 0{\cdot}644.$$

$$m = \{110\},\ A = \{100\},\ l = \{310\},\ s = \{111\},\ e = \{101\}.$$

$$ss\ (111) : (\bar{1}11) = 56^\circ\ 52,\ ee\ (101) : (\bar{1}01) = 65^\circ\ 35'.$$

Twinned on $\{101\}$. Cleavage $\{100\}$, $\{110\}$, good. Brittle. Fracture, uneven. $H = 6\frac{1}{2}$; $G = 4{\cdot}3$. Colour, reddish-brown. Streak, yellowish-brown. Lustre, metallic-adamantine. Translucent; $\omega = 2{\cdot}616$. Birefringence, strong, positive; $\epsilon - \omega = 0{\cdot}287$. Infusible. Insoluble in acids.

With the above description compare crystals from **Alexander County** (North Carolina).

Rutile, the chief compound of titanium, belongs to the same natural group with cassiterite, which it resembles closely in crystalline form and twinning. The larger crystals, usually found in cavities in granite and the crystalline schists, or in quartz, can be easily recognised as striated prisms terminated, like cassiterite, by *s* and *e*, as in Fig. 483. Triplets, as here shown, due to repetition of the twinning upon different faces

of the form, are even more frequent than in cassiterite. Sometimes (as at Graves Mountain, Georgia) the twinning is repeated in such a manner that the twin group returns upon itself and makes a complete ring, as

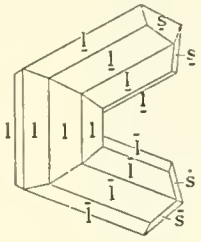

Fig. 485.—Rutile, *l* {310}, *s* {111} ; Triplet twinned on (011).

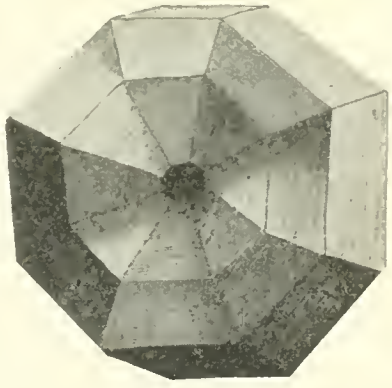

Fig. 486.—Rutile from Georgia ; Octet twinned on (011).

shown in Fig. 486, where the eight individuals do not lie in a plane, but are inclined to each other at 65° 35′ in a zigzag manner. Sometimes, as shown in Fig. 396, p. 249, twin groups of acicular rutile form a reticulated skeletal plate, in which the rays all meet at this angle; delicate examples are found at Tavetsch in Switzerland. Such reticulations are called "sagenite," from *σαγήνη*, a net.

The characteristic heart- and knee-shaped (or kite-shaped) forms due to this twinning (and to twinning on {301}) afford means of recognising rutile under the microscope; it has been frequently identified as microscopic crystals in many slates. Rutile is one of the heavy unalterable minerals which are found as grains and pebbles, in gravels; it may be almost black, but is recognised among other black minerals by the prismatic cleavages combined with the peculiar lustre.

In acicular crystals, which are by no means rare, rutile appears pale yellowish-red, and presents quite a different aspect from the ordinary black or reddish masses or the brilliant metallic crystals in which it is sometimes found. Pieces of rock crystal or smoky quartz containing fine rutile fibres known as "flêches d'amour" (Fig. 487), are polished as ornaments; the latter were described by Pliny under the name *veneris crinis:* "Nigerrimi nitoris continet speciem rufi crinis."

The curious manner in which rutile needles are symmetrically disposed on hexagonal plates of hæmatite (at St. Gothard) has been shown in Fig. 220, p. 86.

Massive rutile, in reddish-black masses, is largely worked at Risör and other places in Norway as an ore of titanium, which is used for colouring glass yellow.

To the same group with rutile and cassiterite belong **polianite**, MnO_2, a steel-gray mineral occurring in small crystals with, and closely resembling the more common hydrate manganite, and **plattnerite**, PbO_2, a rare black massive mineral which is sometimes found in microscopic crystals. To the cassiterite group is added by many authors the

zirconium silicate, zircon, $ZrSiO_4$ (together with thorite, the corresponding thorium silicate, which is isomorphous with it); in its angles and its twinning zircon exactly resembles cassiterite, and this is another case of

Fig. 487.—Rutile in Quartz.

"isomorphism" between bodies which may be chemically unlike. The similarity suggests that the formulæ of this group should be doubled, and that cassiterite is $SnSnO_4$ and rutile $TiTiO_4$.

Among the dioxides of tetravalent elements occurs a remarkable

Fig. 488.—Anatase with Quartz, from Oisans (France).

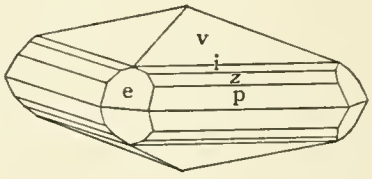

Fig. 489.—Anatase, v {117}, i {116}, z {113}, p {111}, e {101}.

case of polymorphism; TiO_2 is found as no less than three well-defined and beautifully crystallised minerals, rutile, anatase, and brookite.

Anatase.—Oxide of titanium; TiO_2; Ti = 60, O = 40. Tetragonal.

$$a : c = 1 : 1{\cdot}777.$$

$$p = \{111\}, C = \{001\}, e = \{101\}, v = \{11\bar{7}\}, A = \{100\}.$$

$$pp\,(111) : (1\bar{1}1) = 82^\circ\ 9', \quad vv\,(117) : (1\bar{1}7) = 39^\circ\ 30'.$$

Cleavage C, *p*, good. Brittle. Fracture, sub-conchoidal. H = $5\frac{1}{2}$; G = 3·9. Brownish-yellow. Streak, colourless. Lustre, metallic-adamantine. Translucent; $\omega = 2{\cdot}554$. Birefringence, strong, negative; $\omega - \epsilon = 0{\cdot}061$. Infusible. Insoluble in acids.

With the above description compare crystals from **Bourg d'Oisans** (Dauphiné.)

Brookite.—Oxide of titanium; TiO_2; Ti = 60, O = 40. Orthorhombic.

$$a : b : c = 0{\cdot}841 : 1 : 0{\cdot}944.$$

$$i = \{210\}, t = \{021\}, y = \{104\}, z = \{112\}, n = \{121\}, A = \{100\}, m = \{110\},$$
$$e = \{122\}, o = \{111\}, x = \{102\}, B = \{010\}.$$

$$mm\,(110) : (1\bar{1}0) = 80^\circ\ 10', \quad ee\,(122) : (\bar{1}22) = 44^\circ\ 23'.$$

Cleavage, *b*, *m*, *c*, imperfect. Brittle. Fracture, conchoidal. H = $5\frac{1}{2}$; G = 4. Red. Streak, gray. Lustre, metallic-adamantine. Translucent. Birefringence, positive; $\beta = 2{\cdot}53$; $\gamma - \alpha = 0{\cdot}16$. Axial plane (010) for blue, (001) for red light. Acute bisectrix normal to A. 2E = 30°. Uniaxial for a colour between yellow and green. Infusible. Insoluble in acids.

With the above description compare crystals from **Tremadoc** (North Wales).

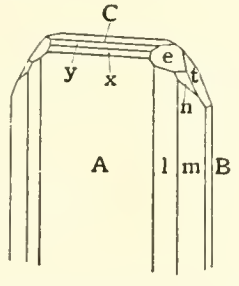

Fig. 490.—Brookite, A {100}, B {010}, C {001}, *m* {110}, *l* {210}, *y* {104}, *x* {102}, *e* {122}, *t* {021}, *n* {121}.

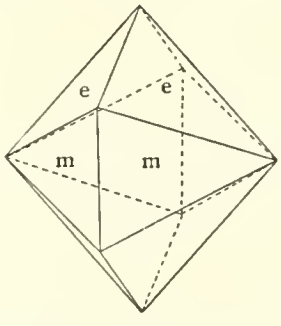

Fig. 491.—Brookite (Arkansite), *e* {122}, *m* {110}.

Anatase, or octahedrite, like rutile, is tetragonal, but the angles are not those of rutile, neither can it be referred to the same axes. The name was given by Haüy from the Greek *ἀνάτασις*, *erection*, to indicate that the *c*-axis is longer than that of rutile. The common habit is the simple square bipyramid of Fig. 488. A second habit is the flatter one of Fig. 489, in which, referred to the above axes, the faces have the following indices, $v = \{117\}$, $i = \{116\}$, $z = \{113\}$, $p = \{111\}$, $e = \{101\}$. Anatase has a metallic-adamantine lustre even superior to that of rutile, and is only found in isolated crystals; they are often black.

Brookite belongs to the orthorhombic system, is also found almost solely in brilliant crystals with the same metallic-adamantine lustre, and also occurs in two distinct habits—(1) The thin tabular crystals of Fig. 490 (formerly found in cavities in diabase near Tremadoc, North Wales); these have the large macro-pinakoid A vertically striated and are terminated by brilliant faces. (2) The six-sided bipyramids of Fig.

491 ; these are a combination of {110} and {122} ; large black crystals of this type have been found in the elæolite-syenite of Magnet Cove, Arkansas, and are called "arkansite."

The Tremadoc crystals when very thin are of a bright red colour by transmitted light, and, being transparent, are excellently adapted to show the peculiar crossing of the optic axial planes for different colours described on p. 156. The acute bisectrix for all colours is perpendicular to A {100}, but the axial plane for red light is horizontal, while that for blue light is vertical. If any such crystal of brookite placed between crossed nicols on the microscope stage be viewed through a spectroscope, a black band will be seen in the green part of the spectrum corresponding to the light for which the mineral is uniaxial.

There is a slight difference in the specific gravity of the three modifications of TiO_2—rutile, 4·2 ; anatase, 3·9 ; brookite, 4·0. All three modifications have been produced artificially in a manner similar to that mentioned on p. 362 as the process by which cassiterite has been manufactured, the action of steam on fluoride of titanium ; the three modifications are obtained at different temperatures. Rutile appears to be the most stable of the three, for aggregates of rutile needles in the form of brookite (Fig. 491) have been found at Magnet Cove, and in the form of anatase in Brazil.

It is remarkable that wherever one of these minerals is found it is accompanied by one or both of the others ; brookite, for example, occurs with anatase at Tremadoc, with rutile at Magnet Cove. This is not at all usual with polymorphous compounds.

The only other metallic dioxide of at all frequent occurrence is **pyrolusite**, MnO_2, a soft, black, amorphous mineral (H = 2), which is largely worked as an ore of manganese ; it appears to be usually a result of the dehydration of manganite, and crystals which have been regarded as pyrolusite are probably pseudomorphs after manganite ; true crystals of MnO_2 have been distinguished above as polianite.

No crystalline hydrates of the dioxides are known among minerals.

SECTION XI

THE DIOXIDES—*(Continued)*

QUARTZ AND THE OTHER VARIETIES OF SILICA

Quartz.—Oxide of silicon; SiO_2; Si = 46·7, O = 53·3. Hexagonal; symmetry, trigonal holoaxial. Common form, hexagonal prism, terminated by R $\{100\}$, z $\{22\bar{1}\}$.

$$a : c = 1 : 1{\cdot}100.$$

$$R = \{100\},\ z = \{22\bar{1}\},\ m = \{2\bar{1}\bar{1}\},\ s = \{41\bar{2}\},\ x = \{4\bar{1}2\}.$$

$$mR\ (2\bar{1}\bar{1}) : (100) = 38^\circ\ 13',\ Rz\ (100) : (22\bar{1}) = 46^\circ\ 16',\ Rs\ (100) : (41\bar{2}) = 28^\circ\ 54'.$$

$$zs\ (22\bar{1}) : (41\bar{2}) = 28^\circ\ 54',\ sx\ (41\bar{2}) : (4\bar{1}2) = 25^\circ\ 57'.$$

Twinned on axis [111] or on face $(10\bar{1})$. Cleavage R $\{100\}$, very imperfect. Brittle. Fracture, conchoidal. H = 7; G = 2·65. Colourless. Streak, white. Lustre, vitreous. Transparent; $\omega = 1{\cdot}544$. Birefringence, positive, weak; $\epsilon - \omega = 0{\cdot}009$. Rotatory polarisation strong; for 1 mm. thickness, line A, 13°; line D, 22°; line G, 43°. Infusible before the blowpipe. Insoluble in acids.

With the above description compare crystals from **Herkimer County** (New York).

Quartz is not only the most common, but, from every point of view, one of the most interesting of minerals. The beauty of

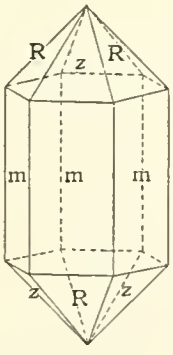

Fig. 492.—Quartz, m $\{2\bar{1}\bar{1}\}$, R $\{100\}$, z $\{2\bar{1}2\}$.

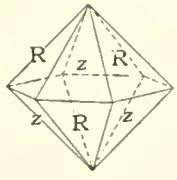

Fig. 493.—Quartz, R $\{100\}$, z $\{2\bar{1}2\}$.

the transparent glassy crystals and their regular geometrical form attracted attention from the very earliest times; it was known to the ancients by the name κρύσταλλος (ice), and was supposed by them actually to be ice. As was mentioned on p. 11, it furnished Steno with the material for his observations on the constancy of angles in crystals, and

subsequently no mineral has been the subject of more crystallographic study. It has also been employed in countless investigations upon optical, electrical, magnetic and other physical problems. Some of its varieties, such as amethyst, cairngorm, and rose quartz, have always been prized as ornamental stones. It is cut into gems, ornaments, balance weights, spectacle glasses, prisms, and lenses; is fused and drawn into the finest threads and used in the place of silk fibres for delicate physical experiments; in grains and powder it is a valuable cutting and polishing material; and it is used in the manufacture of glass and porcelain.

Quartz is also the most ubiquitous of minerals and has been formed under the most diverse conditions both by igneous and aqueous agencies; it is a universal constituent of granite and other acid rocks of igneous origin; it permeates all manner of geological formations as an aqueous infiltration; and is the common veinstuff of lodes and veins; in the form

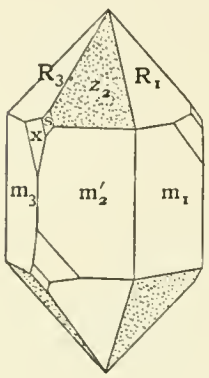

Fig. 494.—Quartz, m $\{2\bar{1}\bar{1}\}$, R $\{100\}$, z $\{2\bar{1}\bar{2}\}$, s $\{1\bar{2}\bar{4}\}$, x $\{\bar{1}\bar{2}\bar{4}\}$.

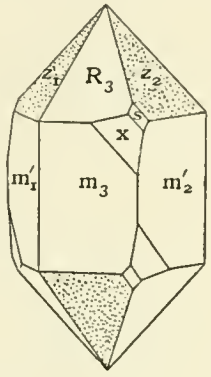

Fig. 495.—Quartz, turned through 60° from the position of Fig. 494.

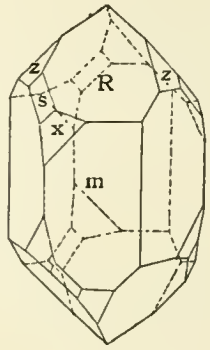

Fig. 496.—Quartz, left-handed crystal of trigonal habit.

of grains it constitutes almost the whole mass of the sands and sandstones so widely distributed upon the earth's surface.

The name quartz is a German word of unknown origin, and has come into universal use in all languages since the sixteenth century.

The regular shape and the smoothness of this mineral are described by Pliny: "Quare sexangulis nascatur lateribus non facile ratio inveniri potest; eo magis quod neque mucronibus eadem species est, et ita absolutus est laterum laevor, ut nulla id arte possit aequari."

No more instructive example exists of the principles of crystalline symmetry, both geometrical and physical. The ordinary crystals, when doubly terminated, resemble a combination of hexagonal prism and bipyramid (Fig. 492); sometimes (as at Alston Moor) the form is a simple bipyramid (Fig. 493). The trigonal character of the symmetry is, however, displayed by many crystals, such as those which are common in the metalliferous veins of Schemnitz in Hungary, in which at each end three alternate faces of the pyramid are larger than the remaining three (Figs. 496, 501, 511), showing that the hexagonal bipyramid consists of two rhombohedra, R $\{100\}$, and its inverse, z $\{22\bar{1}\}$; sometimes, *e.g.*, from Hungary and Brazil, the crystals are terminated by only the one

rhombohedron R, and at some localities (*e.g.* from Bristol, small brown crystals enclosing clay) the mineral has been found as simple rhombohedra, R, which resemble cubes, the rhombohedron angle (100) : (010) being 85° 46′. Further, though the cleavage is hard to obtain by fracture, a quartz crystal, when heated and plunged suddenly into cold water, breaks up with an imperfect cleavage along the same rhombohedron of 85° 46′. The trigonal character being thus established, the holoaxial symmetry is clearly shown by such crystals as Fig. 494, in which the faces *x* only occur on *alternate* corners and constitute the trigonal trapezohedron of Fig. 189. The same combination is represented in Fig. 495 turned about the principal axis through an angle of 60° or 180°, in order to bring it into the position adopted in their figures by most authors; and the position of Fig. 495 will be generally retained in the figures of quartz. Possessing no plane or centre of symmetry, the crystals are enantiomorphous. Fig. 497 represents what is conventionally called a right-handed crystal, and Fig. 498 the corresponding left-handed crystal; the two varieties are about equally

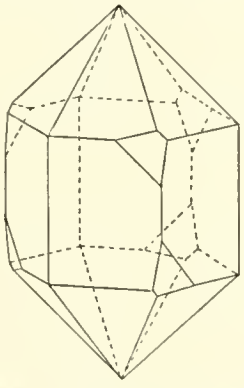

Fig. 497.—Quartz, right-handed crystal.

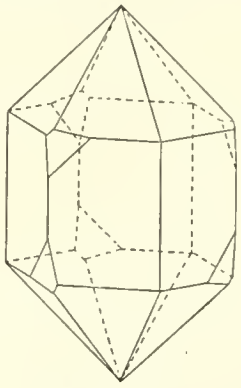

Fig. 498.—Quartz, left-handed crystal.

common. They may be distinguished in three ways: (1) by the position of the *x* face, which in a right-handed crystal lies below the right-hand corner of R; (2) by the direction of the zone *zsxm*, which in a right-handed crystal follows the direction of the thread of a right-handed screw at both ends of the crystal (Fig. 495); and (3) by the direction of the striæ on *s*, which are parallel to the edge *s*R, and therefore follow the direction of the zone *zsx* (as in the left-handed crystal, Fig. 501). By means of these striæ it is easy to determine the right- or left-handed character of any crystal on which *s* exists, even when *x* is absent and when R and *z* cannot be distinguished. The face *s* is often, from its shape, called the "rhomb-face," lying in the zones R*m* and *zm*; it belongs to a trigonal bipyramid. Faces, like *x*, which belong to a trigonal trapezohedron are often called the "plagihedral" or "trapezohedral" faces. The striations on *s* serve to distinguish the forms R and *z*, since they are always parallel to the edge *s*R; these forms often differ also in surface characters, R being bright, and *z* dull; R is also marked with little curved triangles, as in Figs. 501, 502, 505. When other more acute rhombohedra are present, those which are below

R have brilliant, though often rounded, faces; those below z are horizontally striated or dull (M, e in Fig. 507).

From what has been said it might appear that trapezohedral faces necessarily lie below R; they are sometimes found below z. "Positive" trapezohedral faces, situated below R, are more frequent than "negative" trapezohedral faces which are situated below z. Right-handed crystals display positive trapezohedra under the right corner of R, negative trapezohedra under the left corner of z. In left-handed crystals the positive trapezohedra are under the left corner of R, negative under the right corner of z. The two sorts of crystals are, in fact, in all respects the reflections of each other, and the trapezohedral faces are grouped about s in each. Complementary right and left

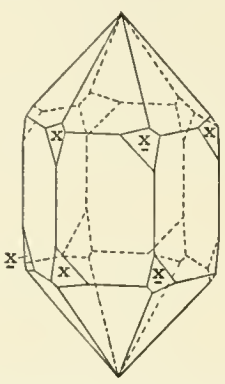

Fig. 499.—Quartz, right-handed, twinned on axis [111].

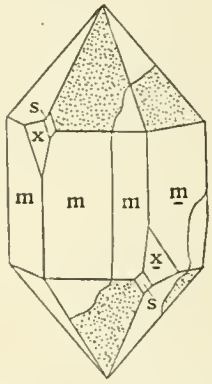

Fig. 500.—Quartz, right-handed, twinned on axis [111].

faces would have the positions of $x\underline{x}$ in Fig. 503; but when such faces occur upon the same crystal, it is invariably found to be, not a single crystal, but an interpenetrant twin.

The twinning of quartz can be deciphered by means of the faces sx, and is found to be extraordinarily varied.

1. *Twin axis* [111] parallel to the prism edge; interpenetrant twin.—The right-handed crystal of Fig. 495 being turned through 180° about the vertical, the axis [111] is brought into the position of Fig. 494. Two such crystals, interpenetrating completely, yield Fig. 499, in which the twinning is disclosed by the appearance of x (and s) upon *adjacent* corners. In Fig. 499 the edges and corners which are developed are those that carry the faces x of one individual and $\underline{x}$ of the other; if they had been those edges of Figs. 494 and 495 from which x is absent, the crystal would resemble Fig. 492. Even in this case, however, the twin structure may often be recognised by the fact that R of one crystal coincides with z of the other; a pyramid face may consist, for this reason, of parts which are bright, belonging to R of one individual, alternating with parts which are dull, belonging to z of the other individual. A curious pattern may then be delineated upon the pyramidal terminations, which marks the boundaries of the two interlacing crystals, as shown in Fig. 500. These may interpenetrate quite irregularly, or the crystal may even be an individual which contains only one small corner of a second individual

twinned with it. The presence of the face s or x upon any two adjacent corners is sufficient to betray the twinning. Two *left-handed* crystals may be twinned together, according to this law, and give rise to similar

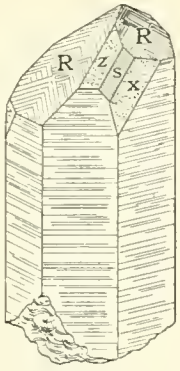

Fig. 501.—Quartz, left-handed crystal.

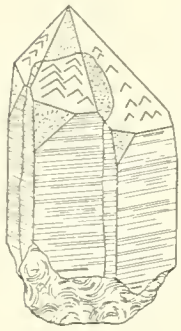

Fig. 502.—Quartz, left-handed, twinned on axis [111].

twins (Fig. 502); in these the striations on s are of the sort shown on Fig. 501. In Fig. 502 the R faces can be recognised by their triangular markings, and the z faces by their dulness.

2. *Axis of alternating twinning* [111] parallel to the prism edge; interpenetrant twin.—Let the crystal of Fig. 497 be united, not with the right-handed crystal of Fig. 494, but with the left-handed crystal of Fig. 498, which may be derived from it by a half-turn about the vertical axis followed by reflection over the horizontal plane. An intergrowth is then obtained of a right- with a left-handed crystal (Fig. 503), such that the R faces of the two individuals coincide. The crystal as a whole is now symmetrical to vertical planes passing through the centres of its faces, *i.e.* to the faces of the prism $\{10\bar{1}\}$, which would truncate the edges of the prism m. This law is, therefore, usually described as twinning about $\{10\bar{1}\}$. As in the first law the interpenetration may be quite irregular, but twinning will be betrayed by the development of right-handed faces, x, or of s faces with right-handed striations on some corners, and of left-handed faces on others. On account of its frequent occurrence in crystals from Brazil this is sometimes called the *Brazil law*. Here there is no tesselation of the R and z faces, as in Fig. 500. Juxtaposition according to this law is shown in Fig. 237.

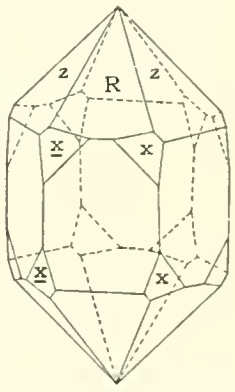

Fig. 503. — Quartz, alternating twin on axis [111].

3. *Twin plane* (111) perpendicular to the prism edge; interpenetrant twin.—Crystals which resemble the last in containing both right and left quartz are sometimes, though rarely, found in which the two x faces occur not upon adjacent corners, as in Fig. 503, but upon the same corner, as in Fig. 504. This figure represents an intergrowth of Fig. 497 with Fig. 498, after the latter has been turned through 180° about the principal axis; the same result is obtained by reflecting Fig. 497 over a

horizontal plane, and the law may, therefore, be described as twinning about the plane (111).

Very many crystals of quartz, when carefully examined, bear evidence of twinning according to one or other of the above laws; if the crystal consists entirely of right-handed or of left-handed material the twinning is about an axis alone (Law 1); if it consists of both

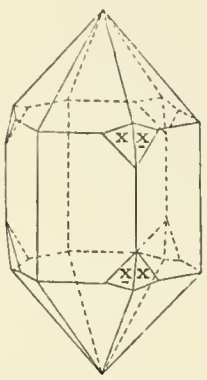

Fig. 504.—Quartz twinned on plane (111).

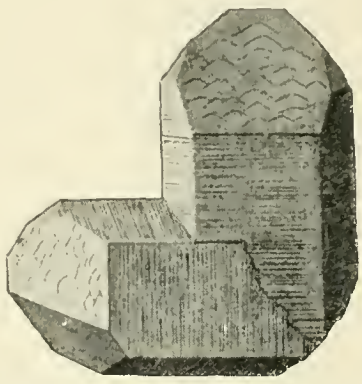

Fig. 505.—Quartz twinned on $(52\bar{1})$. Japan.

right and left quartz the twinning can only be expressed as involving reflection about a plane, and is generally a case of Law 2.

4. *Twin plane* ξ (521); juxtaposition twin.—The projection, Fig. 513, gives the position of the common faces of a right-handed crystal. One very rare form, $\xi\,\{52\bar{1}\}$, there indicated as truncating the pyramid edge R*z*, is inserted because it is of importance as a twin plane. The twins considered above are interpenetrant and have their principal axes coincident; twinning about ξ causes two crystals to unite with their principal axes nearly at right angles to each other.

Here, Fig. 505, the two individuals have one edge R*z* parallel, and their principal axes inclined at 84° 33′. A large number of these have lately been found in Japan; previously only a very few examples were known from a quarry near Bourg d'Oisans in Dauphiné. At both localities the crystals are invariably flattened in the plane which contains the principal axes, and they intersect in a zigzag line. There has been some discussion as to whether the twinning is reflection about the plane ξ, in which case one individual must be right- and the other left-quartz, or hemitropy about the edge R*z* or about the normal to ξ, in which case the two individuals are of the same sort. Generally each individual is found to be itself a Brazil twin, so that the distinction cannot be established. Fig. 506 is from a photograph of a magnificent specimen from Bourg d'Oisans, now in the British Museum.

Figs. 501 and 502 illustrate the sort of faces found upon quartz, with their natural markings. At some localities remarkable forms with very high indices prevail, *e.g.* at Alexander County, North Carolina (Fig. 507). Some of these faces, though perfectly bright and smooth, may be prerosion planes, for the crystals exhibit considerable signs of etching.

It is at such localities that, as a great rarity, the basal plane (111) is occasionally found as a rough surface; it is otherwise unknown in this mineral, and is probably only developed as a prerosion face.

Fig. 506.—Quartz twinned on $(52\bar{1})$, Dauphiné (Brit. Mus.).

Fig. 507, a twin on Law 1, illustrates the difference between the direct and inverse rhombohedra below R and z respectively. In this figure $z = \{2\bar{1}2\}$, $s = \{4\bar{2}1\}$, $u = \{8\bar{4}\bar{1}\}$, $y = \{10\cdot\bar{5}\cdot\bar{2}\}$, $x = \{4\bar{2}\bar{1}\}$, $M = \{4\bar{5}4\}$, $e = \{2\bar{3}2\}$, $W = \{16\cdot\bar{1}\cdot\bar{4}\cdot7\}$, and the dull faces adjacent to M and e are the forms inverse to them, viz. $\{7\bar{2}2\}$ and $\{11\cdot\bar{4}\cdot4\}$.

Mis-shapen crystals of quartz (*cf.* Fig. 9, p. 11) are common and sometimes puzzling, but they may always be deciphered by means of the horizontal striations on the rarely-failing prism faces m.

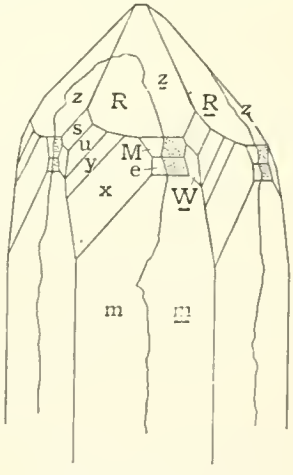

Fig. 507.—Quartz from North Carolina.

Right- and left-handed quartz is also right- and left-handed in the optical sense; if a source of plane-polarised light be viewed along the principal axis of a crystal like Fig. 497, the plane of polarisation is rotated to the right; in a crystal like Fig. 498 to the left. Among minerals quartz may be identified by the characteristic interference figure (p. 162, Fig. 343). When right-quartz and left-quartz overlap, Airy's spirals are seen. A basal section of a crystal twinned according to Law 2 or Law 3 generally shows in some parts a tint which is proved by rotation of the polariser to belong to right-quartz, in some parts the same tint belonging to left-quartz, and in other parts Airy's spirals. The arrangement of the right and left material is sometimes in regular triangular sectors whose bases are the sides of the hexagonal section.

Of course, if the section be extremely thin, as in microscopic preparations of rocks, these effects may not be visible, and the figure will appear to be a normal one.

The electrical properties indicate the holoaxial symmetry in the most striking manner; the principal axis is not polar, but the three horizontal axes of digonal symmetry (which would emerge through the prism edges in Figs. 494 and 495) are polar, and are therefore also axes of pyro-electric polarity; one end of each such axis emerges through a prism edge which carries the faces *sx*; the other end through those prism edges from which these faces are absent. When a crystal is treated by Kundt's method (p. 115) the former edges become, during cooling, negatively electrified, and the latter positively; similarly, a basal section—a mere hexagonal plate—will attract the red lead to three alternate corners of the hexagon and the yellow sulphur to the other three corners.

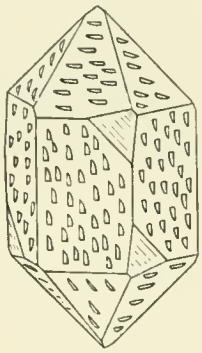

Fig. 508.—Quartz, right-handed, etched with HF.

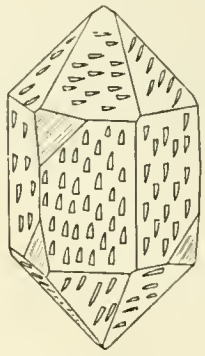

Fig. 509.—Quartz, left-handed, etched with HF.

Etching, both natural and artificial, is equally characteristic. Fig. 508 represents a right-handed, and Fig. 509 a left-handed crystal, etched with hydrofluoric acid; the one figure is a complete reflection of the other. The twinning on Laws 1, 2, and 3 is in-

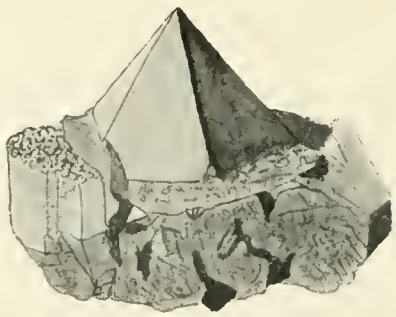

Fig. 510.—Capped Quartz.

Fig. 510*a*.—Cap of Fig. 510.

dicated both in pyro-electric experiments, and in the etching, by like parts of the crystal occupying adjacent, instead of alternate, positions (*cf.* Figs. 499, 503, 504).

There is scarcely any important feature of crystals which is not well

illustrated by quartz. The manner in which a crystal grows in parallel layers is exemplified by the so-called "capped quartz," in which one shell can be separated from another (Fig. 510); the inner kernel has here been coated with a fine deposit of clay, mica, or other material which has prevented the subsequent layer from adhering to it. "Ghost quartz" (Fig. 511) is a transparent crystal, in which such a deposit makes the kernel visible within, although the later shell cannot be separated from it.

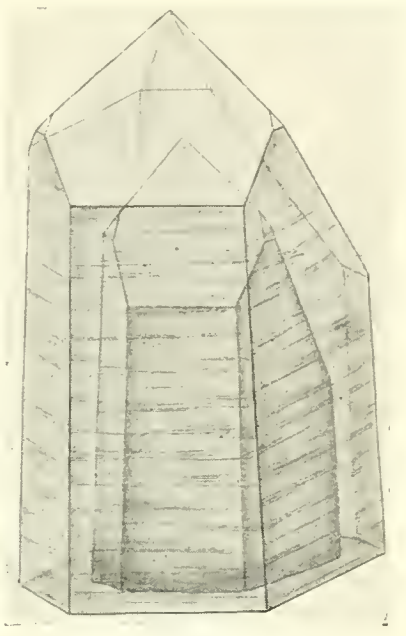

Fig. 511.—Ghost Quartz from Brazil.

A remarkable example of curvature of crystal faces is supplied by "twisted quartz." Sometimes this appears to consist of a single warped crystal, but on close inspection is found to be made up of many individuals, each being twisted through a small angle from the position of its neighbour; their arrangement is really of a spiral character. This must be intimately connected with the symmetry, for the spiral twist is right-handed in the case of right quartz, and left-handed in the case of left quartz. Tschermak regards these as twin growths in which the twin axes are perpendicular to vicinal faces and not to the base, so that successive individuals very nearly coincide. Similarly, in the interpenetration twins described above (Laws 1, 2, and 3), the individuals are sometimes not quite coincident, and the twinning may be then also of a "vicinal" character. There is thus sometimes an inequality of surface on the pyramid faces of the twinned crystals, and especially a twin suture down the prism faces, as shown in Figs. 500, 502, 507.

Intergrowths of right- and left-quartz generally break with a wavy surface, known as the "ripple fracture," which may be due to the same vicinal twinning.

Quartz, having a refractive index near that of balsam, is nearly invisible in thin rock sections in ordinary light; between crossed nicols in sections of medium thickness it yields colours of the first order.

Rock crystal (*Germ.* Bergkrystall) is the colourless glassy quartz, of which the best examples are to be found lining cavities in the crystalline schists, as at St. Gothard and Bourg d'Oisans, in marble, as at the Carrara Quarries, or in sandstone, as at Herkimer County, New York. Enormous crystals have been found in Brazil, Madagascar, and Japan (from which the well-known crystal spheres are turned). Doubly terminated crystals are mostly found in soft materials, such as clays and marls. Glittering crystals of quartz are generally known locally as "diamonds," *e.g.* Bristol, Wicklow, or Lake George diamonds.

Rock crystal often contains enclosures; the "flêches d'amour,"

enclosed hairs of rutile, have been mentioned on p. 363; fibrous actinolite or asbestos is common in Cornish crystals. Cavities (which often have the exact form of the quartz itself, so-called "negative crystals") sometimes

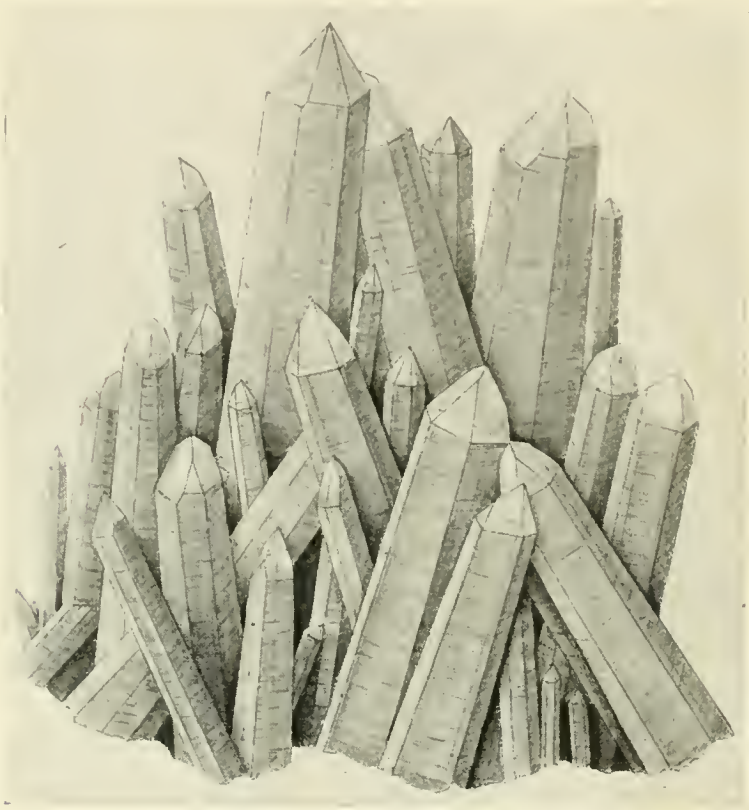

Fig. 512.—Quartz, group from Cornwall (Brit. Mus.).

contain liquid, either water or liquid CO_2, and these not infrequently enclose a movable bubble. The quartz from Herkimer County encloses anthracite. "Avanturine quartz" has a shimmer due to spangles of mica or hæmatite enclosed in it.

Many coloured varieties of quartz are known:—

Amethyst is violet quartz, of which the colour has been attributed to manganese, but it usually changes to yellow on heating. Amethyst is invariably composed of right- and left-quartz, breaks with the ripple fracture, and shows Airy's spirals. By many authors the name is consequently used to denote all quartz having this structure, whatever its colour.

The beautiful masses used for ornamental purposes are found lining geodes and veins in Brazil, or as pebbles in Ceylon. The amethyst from Mursinka, in the Urals, generally contains liquid CO_2, with movable bubbles of the gas.

Smoky quartz includes the yellowish, brownish, and black crystals, of which beautiful specimens have been found in the Alps. Some of the quartz lining cavities in granite is the black variety known as "morion"; in the granite, for example, of Mursinka, and of the Mourne Mountains in Ireland. When cut as a gem the brown and yellow varieties are

generally known as "cairngorm," from the locality in Banffshire, Scotland, where fine examples are found.

Yellow quartz, of a topaz colour, is known as "citrine."

Milk quartz is white and nearly opaque, and is very common among the crystals which line the sides of veins.

Rose quartz, a pale red material used for ornaments, may owe its colour to titanium or to manganese; the fine masses found in granite at Rabenstein in Bavaria are certainly associated with manganese ore. Good pieces are also brought from Finland. Rose quartz is for the most part massive.

True *cat's-eye* is a variety of chrysoberyl, but an opalescent quartz which, when cut *en cabochon*, reflects the peculiar band of light characteristic of the former mineral, is known by the same name. The effect is caused by a fibrous structure, and may be due to silky fibres of asbestos or to quartz replacing them. The beautiful, golden "crocidolite" from Griqualand in South Africa consists largely of quartz replacing a fibrous asbestos.

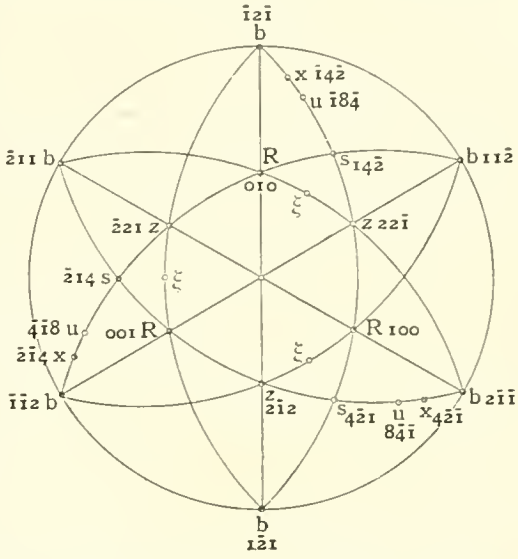

Fig. 513.—Quartz, projection of common forms; left-handed.
$b = m$ of preceding figures.

Owing to the wide diffusion of siliceous solutions, quartz is found replacing (or pseudomorphous after) many minerals; but on account of its own resistance to solvents it is itself scarcely ever altered into other minerals. Most remarkable, therefore, are the pseudomorphs of steatite after quartz found at Göpfersgrün in Bavaria; these are perfect crystals completely transformed into steatite, and are found in a band of that mineral at the junction of granite with crystalline schists; their production is difficult to explain.

Fig. 514.—Agate from Uruguay (Brit. Mus.).

Chalcedony.—Much of the silica which occurs in nature, even much of that which accompanies rock crystal, is an apparently amorphous substance, translucent, having a waxy lustre, specific gravity about 2·6, hardness equal to that of quartz, and an even fracture. This material, chalcedony, appears to have been always deposited from aqueous solution; it fills cavities in decomposed igneous rocks, or lines geodes and veins; it generally has a banded structure (Fig. 514), and varies much in colour from white, yellowish-brown, dark brown, to blue (see under agate, p. 381).

When free to assume a form of its own it is frequently concretionary, mamillary, botryoidal, or stalactitic. The most remarkable specimens are the fantastic, arborescent stalactites formerly found in the Trevascus Copper Mine near Camborne in Cornwall. Wherever silica has been carried away in solution from decomposed silicates chalcedony is apt to be deposited; it is frequently the material of pseudomorphs. Among striking examples may be mentioned the pseudomorphs of white chalcedony after octahedra of fluor from Beeralston in Devonshire, and those of smalt-blue chalcedony after cubes of fluor from Tresztya in Transylvania; large crystals of what looks like stained quartz, formerly found in the iron mine of Haytor in Devonshire, were called "haytorite," and were supposed to be a new mineral; they have been proved to be pseudomorphs of chalcedony after datolite.

Under the microscope chalcedony is found to be crystalline, consisting of minute fibres, which are biaxial and positive, with straight extinction, and elongated along the obtuse bisectrix, *i.e.* in a negative direction; they are therefore quite distinct from true quartz, and chalcedony is not, as was formerly supposed, merely a massive or micro-crystalline quartz.

Considerable attention has been paid to the microscopic characters of massive silica, and other varieties have been distinguished. "*Quartzine*" is the name given to one in which the fibres are biaxial and positive, but elongated along the *acute* bisectrix; this may be merely a different habit of chalcedony. The blue pseudomorphous material from Tresztya just mentioned appears to consist partly of a mineral having a specific gravity 2·04, and refractive index 1·446; identical, therefore, in these respects with opal, but fibrous, and, like quartzine, elongated in the positive direction. It has been called "*lussatite*" from a locality in Puy-de-Dôme, where it also occurs.

It was mentioned above (p. 186) that the circular polarisation of quartz can be simulated by a spiral pile of plates of biaxial mica; it has been suggested that rock crystal may really consist of a spiral arrangement of crystalline plates of chalcedony which are too fine to be distinguished; such a structure might account for both the trigonal symmetry and the rotatory polarisation of quartz. Some quartz crystals are certainly biaxial in parts. It is, however, difficult to see how this structure could account for the polar character of the three digonal axes.

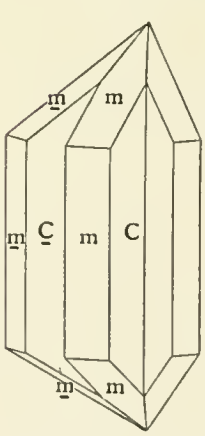

Fig. 515.—Tridymite, C {0001}, *m* {10$\bar{1}$0}.

Tridymite.—This mineral, found in colourless hexagonal scales and plates lining cavities of an andesite from Mexico, and subsequently found in the trachyte of the Siebengebirge and other localities, is certainly quite distinct from quartz. It has a basal cleavage; H = 7, G = 2·29; refractive index, 1·477. The name alludes to its common tendency to form the triplets of Fig. 515. The apparent hexagonal plates are also in reality pseudo-symmetric twins

of biaxial, probably orthorhombic, material, which only becomes uniaxial at a temperature of 130°. Tridymite is probably identical with a remarkable orthorhombic (?) silica named "asmanite," which was found by Maskelyne in the meteoric stone of Breitenbach, quartz itself being quite unknown in meteorites. Tridymite, unlike quartz, is soluble in sodium carbonate; it may possibly be isomorphous with brookite.

Opal.—Hydrated silica; $SiO_2 + nH_2O$. Amorphous. Brittle. Fracture, conchoidal. $H = 6$; $G = 2{\cdot}1$. White. Streak, white. Lustre, vitreous, or resinous. Translucent; $\mu = 1{\cdot}455$. Infusible, but yields water. Soluble in potash.

With the above description compare common white opal from **Cornwall.**

Opal shows no trace of crystallisation, but is only found in bands and layers, in botryoidal or stalactitic masses, filling cavities, pseudomorphous after other minerals, or replacing organisms; it has been deposited in many places to which siliceous waters have had access, especially in decomposed igneous rocks, and frequently accompanies quartz and chalcedony. The proportion of water which it contains varies considerably; the ordinary amount is from 5 to 10 per cent; some varieties contain as much as 30 per cent; some are practically anhydrous. It can generally be recognised by its greasy lustre, and identified by the low density and refractive index as compared with the other varieties of silica. In these respects the lussatite mentioned on p. 378 is the only silica which possesses the same properties as opal. Opal, when cut and polished with a plane surface, may very conveniently be distinguished from quartz by means of the total reflectometer.

The description given above applies to the common white opal, but two other varieties merit particular attention.

Hyalite is a perfectly transparent, colourless, and glassy opal, usually found as a botryoidal or mamillary incrustation; it contains a small proportion of water. The little hemispheres detached from botryoidal groups are birefringent, and give a black cross under the microscope in parallel light; but this effect is probably due to the strain introduced when the substance solidified from solution. Good specimens of hyalite occur in cavities and amygdules of basalt at Waltsch in Bohemia.

Precious opal is the name given to the varieties which exhibit a beautiful play of colours; this property, in spite of the inferior hardness, low refractive power, and opacity of the stone, makes it one of the most valuable of gems. No other mineral presents such a varied and brilliant play of colours. The transparent opals are of no particular beauty; it is the opaque and translucent varieties, which yield by reflected light the remarkable mother-of-pearl colours which have made the opal famous. The colours are interference effects due in the precious opal to the presence of thin films. Whether these films are mere cavities (cracks filled with air), or fine interpositions of opal whose refractive index differs slightly from that of the main mass, is not quite certain. The latter explanation is probably the correct one; but in any case the films or cracks seem to have resulted

from the loss of water during solidification of a jelly-like material, and the difference of refractive index may depend upon the difference in the proportion of water.

Sometimes the effect is that of vari-coloured spangles; sometimes all the opal from a certain locality presents a single prevalent colour. Three localities afford very typical specimens. Until modern times most precious opal came from the neighbourhood of Czerwenitza in Hungary, where it is found disseminated through an altered trachyte, and consists of small spangles of very varied shades of yellow, green, blue, and red. Specimens often consist largely of the gray matrix. Recently Queensland has produced a precious opal which occurs as nodules and pipe-shaped pieces in a brown, jaspery limonite; the best have come from Barcoo River; they generally have a prevalent blue and green colour. From Zimapan in Mexico a somewhat different variety, the so-called "fire opal," has been obtained for the last century; this is a fiery-red opal without much play of colour, which fills cavities in a porphyritic trachyte.

Other names employed for varieties of opal are "wood opal," which is wood converted into opal and still preserving its characteristic fibrous structure; "menilite," or liver opal, curious concretionary forms of an opaque, grayish-brown substance found in shale at Menilmontant near Paris; "siliceous sinter," the globular, botryoidal, or platy encrustations deposited from hot siliceous waters; this is sometimes fibrous, stalactitic, porous, or even powdery; the varieties range from the colourless, glassy hyalite to the beautiful red, blue, and yellow crusts which fringe the geyser pools in the Yellowstone Park; the siliceous sinter of the Iceland, New Zealand, and Yellowstone Park geysers is sometimes known as "geyserite"; it is frequently almost powdery.

From what has been said above it will be seen that all chalcedony and opal, and much of the quartz, is deposited where aqueous solutions have permeated decomposing igneous rocks and carried away silica in solution. Two or three of these minerals frequently unite in the same mass, and numbers of special names have been given both to coloured varieties of each and to their mixtures.

"Jasper" is really a mixture of quartz with red or yellow hydrates of iron or with clay, so densely disseminated as to make the quartz quite opaque and creamy; the most beautiful varieties are the deep red brought from Siberia, or found as pebbles on the plains of Argos in Greece; and the rich yellow brought from India and Smyrna. The "riband jasper" of the Urals consists of parallel, straight bands of reddish-brown and sage-green material.

The chief coloured varieties of chalcedony are "carnelian" (*Germ.* Carneol), translucent red with a waxy lustre; "sard," brownish-red with a more horny appearance; "plasma," a leek-green chalcedony; "chrysoprase," an apple-green variety found in Silesia; the name "prase" belongs to green *quartz*, in which the colour is generally due to enclosed chlorite; the colour of chrysoprase is probably due to

nickel. "Blood-stone" or "heliotrope" is plasma spotted with blood-red jasper.

"Agate."—This name includes the banded and variegated chalcedonies; these have generally been deposited layer by layer on the interior of amygdules and cavities in decomposing igneous rocks. The bands follow the irregular contours of the cavity, and, when the agate nodule is cut across, present a beautiful succession of undulating or zigzag lines of different colours (Fig. 514); the material has probably been deposited by infiltrating solutions, which (by endosmose?) have penetrated the layers first laid down upon the sides of the cavity, and have formed successive layers, shell within shell, until the cavity has been filled. An aperture by which the liquid has escaped is sometimes visible on one side of the nodule. Sometimes the centre of the geode is occupied by crystallised quartz; sometimes it is an empty cavity or is filled with water. The successive bands consist for the most part of differently coloured chalcedony, carnelian, jasper, amethyst, and rock crystal, and they may be so fine as to be indistinguishable except with the microscope. According to the form of their markings some agates are distinguished by the name of "ruin agate," "fortification agate," and "eye agate"; according to their material as "carnelian agate" and "jasper agate."

"Onyx" is agate in which the successive layers are parallel bands sufficiently flat to fit them for use as cameos in which the subject is cut in the material (usually white) of one layer upon that of the succeeding layer as background. Sometimes, and especially in the South American agates, a nodule consists of curvilaminar agate in the upper part, while the lower half, where the solution has been able to lie in horizontal layers, consists of horizontally banded onyx. Onyx which contains red bands of carnelian or sard is known as sardonyx.

"Moss agate" (Fig. 400) is chalcedony filled with dendritic inclusions of chlorite, manganese oxide, or other minerals.

"Flint" contains sponge spicules and is of organic origin; it often contains crystallised quartz in its cavities. "Hornstone" and "chert" are names given to compact flinty varieties of chalcedony; the latter is generally also of organic origin.

The best agates were formerly found as amygdaloids in melaphyre in the neighbourhood of Oberstein on the Nahe, where the great agate-cutting works have now existed for more than 400 years; but the finest specimens now come from Rio Grande do Sol and Uruguay in South America, where they occur under similar conditions, together with quartz, citrine, amethyst, and carnelian. Fig. 514 represents a section of one of these amygdaloids; the prevailing colour of these South American agates is usually pale grayish-purple. Fine agates are also found in the basalt, and as pebbles on the beach at Montrose in Forfarshire. Peculiar are the chocolate-brown jasper-agates found near Cairo in Egypt.

SECTION XII

THE ALUMINATES, ETC.

THE SPINEL GROUP

Spinel.—Aluminate of magnesium; $MgAl_2O_4$; $MgO = 28{\cdot}2$, $Al_2O_3 = 71{\cdot}8$. Cubic; holosymmetric. Common form, octahedra. Twinned on (111). Cleavage {111}, imperfect. Brittle. Fracture, conchoidal. H = 8; G = 3·5. Red. Streak, white. Lustre, vitreous. Transparent. Refraction, high; $\mu = 1{\cdot}715$. Infusible. Soluble with difficulty in sulphuric acid.

With the above description compare crystals from **Ceylon**.

Spinel in the red varieties found in the East (Burma, Ceylon) was prized as a kind of ruby from very early times; it has generally been known to jewellers by the name "balas ruby," and the two minerals were not distinguished until the time of Romé de l'Isle (1783).

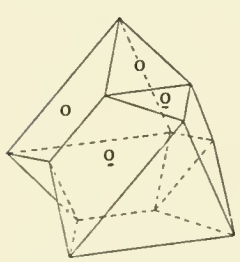

Fig. 516. — Spinel, twinned on (111).

Although the two minerals belong to different systems, a ruby which is a combination of {111} and {100} may easily be confused with a flattened octahedron of spinel. The latter is distinguished by the absence of well-defined cleavage, and of the triangular striations which mark the basal pinakoid of ruby, as well as by its inferior hardness and density. The small crystals of spinel found in the gem-bearing sands of Ceylon are usually simple octahedra which sometimes have their edges truncated by the dodecahedron. The typical "spinel twins" (Fig. 516), with twin plane (111), are very common.

The rounded edges of spinel are not merely due to rolling in sands and gravels, for even when found in the limestone from which they are washed out they often have rounded edges; the crystal faces also often have a platy corroded appearance, and this characterises other minerals (pyroxene, idocrase, etc.) found in similar limestone. A blue spinel found in limestone at Åker in Sweden shows marked corrosion, and this variety is further peculiar as being of *cubic* habit.

Spinel is one of the few cubic minerals which exhibit no birefringence; its isotropic character and absence of pleochroism also

serve to distinguish transparent crystals and facetted stones of spinel from ruby.

"Precious spinel," *i.e.* the crystals suitable for gems, exists in three colours—spinel ruby, the red; almandine spinel, the violet; and rubicelle, the orange-red. The analyses of red spinel show iron replacing magnesium, and traces of chromium to which the colour is doubtless due.

Crystals of pure spinel obtained artificially by the action of aluminium chloride and steam upon red-hot magnesium, or the minute crystals found in basic iron slag, are absolutely colourless.

A Noteworthy Locality:

Vesuvius. — Lustrous black octahedra of iron-magnesia spinel (pleonaste), with edges truncated by the dodecahedron, occur with pale-green augite, mica, and idocrase in the ejected blocks of Monte Somma.

Magnetite.—Ferrate of iron; $Fe''Fe_2'''O_4$; $FeO = 31{\cdot}0, Fe_2O_3 = 69{\cdot}0$. Cubic; holosymmetric. Common form, octahedra and dodecahedra. Twinned on (111). Parting, {111}. Brittle. Fracture, uneven. H = 6; G = 5·2. Black. Streak, black. Lustre, metallic. Opaque. Magnetic and sometimes polar. Fusible with difficulty. Soluble in hydrochloric acid.

With the above description compare crystals from **Nordmarken** (Norway).

Magnetite (*Germ.* Magneteisen, *Fr.* Fer oxydulé) is a mineral which has been known from very early times chiefly on account of its remarkable magnetic property. "Quid enim mirabilius? Aut qua in parte Naturae major improbitas? Quid lapidis rigore pigrius? Ecce sensus manusque tribuit illi" (Pliny). Pliny also tells a tale of its discovery by the shepherd Magnes, whose shoe-nails and staff were attracted by the rock on Mount Ida; but the name may really be derived from Magnesia, as a locality where it was found.

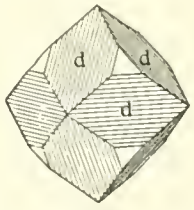

Fig. 517.—Magnetite, {110}, {111}.

The modern importance of the mineral is as one of the most valuable ores of iron; it is worked on an enormous scale in Scandinavia.

Beautiful large isolated octahedra of magnetite are found in the chlorite and talc schists of the Alps.

At Nordmarken in Norway brilliant dodecahedra, or combinations of {110} and {111} of dodecahedral habit (Fig. 517), occur in the crystalline schists. Very characteristic are the striations on the dodecahedron faces; these are parallel to the longer diagonals, and are due to a platy structure parallel to the octahedron. Spinel twinning (Fig. 516) is common, and leads to twin lamellæ, which are probably the cause of the platy structure, and of the octahedral parting. Crystals rich in combinations of various forms have been described, but these are rare. Ordinary magnetite is massive or granular, as, for example, at the Scandinavian iron mines, Taberg, Arendal, etc. The largest masses of

"lodestone" have been found in the Urals and the Altai Mountains; pieces of magnetite sometimes exhibit a north and a south pole. Ordinary emery contains much magnetite.

As a heavy mineral, not prone to alteration, magnetite is one of the substances that become mechanically separated in alluvial deposits

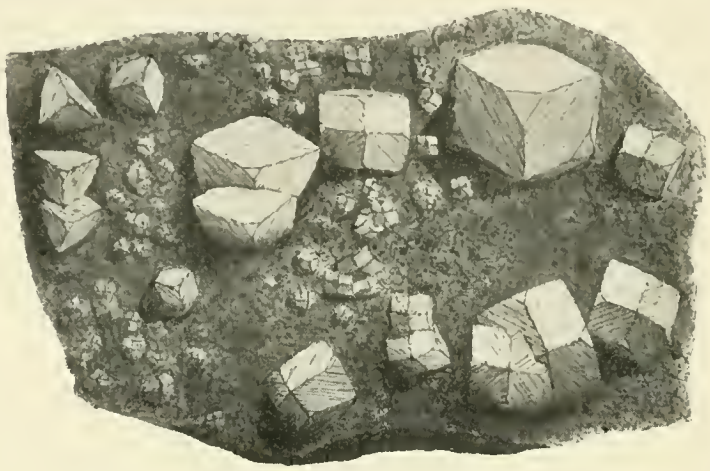

Fig. 518.—Magnetite from Nordmarken (Norway).

and is sometimes found as a magnetic sand. Magnetite and hæmatite both occur as excessively thin dendritic deposits in the cleavage laminæ of mica, where they may be sufficiently thin to be translucent.

In whatever form the mineral occurs, it may always be identified by its magnetism; the only other mineral which possesses the property in the same degree is ferriferous platinum. In a crystal of magnetite the position of the magnetic poles has no particular relation to the form of the crystal.

Some Noteworthy Localities:

Arendal (Norway).—Large beds of magnetite occur in the gneiss, crystalline schists, and limestone; the magnetite is usually granular and accompanied by pyroxene, amphibole, garnet, and calcite. The cavities in the rock are sometimes lined with brilliant dodecahedral crystals of magnetite (Fig. 518).

Zillerthal (Tyrol).—Large octahedra perfectly formed on all sides occur in a compact chlorite slate; many of these are spinel twins. Associated with this occurrence are minute crystals in a foliated limestone.

The members of this group all conform to the type $R''R'''_2O_4$, and may be regarded as cubic aluminates and ferrates of divalent metals, together with the corresponding chromium compounds. The chief minerals in the group are—

Spinel	$MgAl_2O_4$
Gahnite	$ZnAl_2O_4$
Magnetite	$FeFe_2O_4$
Franklinite	$(Zn, Mn)Fe_2O_4$
Chromite	$FeCr_2O_4$

All these are found well crystallised, and generally of an octahedral habit. To them must be added a rare mineral, **magnesioferrite**, $MgFe_2O_4$, found as a sublimation product, with hæmatite, in the fumaroles of Mount Vesuvius, and a black mineral named **jacobsite**, $MnFe_2O_4$, found in small octahedra in calcite at the manganese mines of Jakobsberg in Sweden.

The mutual replacement of Mg, Fe, Zn, Mn among the divalent, and of Fe, Mn, Cr, Al among the trivalent metals is common, and is indicated not only by the isomorphous mixtures which this group contains, but also by a whole series of independent minerals. Thus amongst the aluminates, or spinels proper, may be distinguished :—

Magnesia spinel or **spinel ruby** . .	$MgAl_2O_4$
Magnesia iron spinel or **pleonaste** . .	$(Mg, Fe)Al_2O_4$
Chrome spinel or **picotite** . . .	$(Mg, Fe)(Al, Fe, Cr)_2O_4$
Iron spinel or **hercynite** . . .	$FeAl_2O_4$
Zinc spinel or **gahnite**	$ZnAl_2O_4$

Gahnite contains iron, replacing both the zinc and the aluminium ; and other such mixtures are common. Even the colour of the spinel ruby is due to intermixture with a small proportion of the chromium compound, as shown by the following typical analysis of a Ceylon crystal :—

Al_2O_3	Cr_2O_3	FeO	MgO	SiO_2
69·01	1·10	0·71	26·21	2·02

Most of the spinels are stable compounds, and occur in good crystals : pleonaste (or ceylonite) as dark green or black octahedra of higher specific gravity than spinel, chiefly as a constituent of garnetiferous gneisses and metamorphic rocks ; picotite generally as heavy black grains (G = 4) in olivine rocks (lherzolite, etc.), and in serpentine, sometimes as minute inclusions in olivine ; hercynite as black magnetic specks in the Saxon granulites ; gahnite occurs in greenish or black octahedra with a somewhat greasy lustre in a talc-schist at Falun in Sweden, where it originally received the name of automolite (or "the deserter") from the unusual surroundings in which a zinc mineral there finds itself ; also in the zinc mines of New Jersey.

Among the other members of the spinel group, **franklinite** is somewhat allied to gahnite in composition ; it is a typical mineral of the Franklin Furnace Mine (New Jersey), where it occurs in large black octahedra with rounded edges with the red oxide, zincite, and with green willemite, the silicate of zinc, and in sufficient quantities to be worked as an ore of that metal. Much of the ore is in fact a granular mixture of these three minerals. Franklinite is slightly magnetic.

One of the most important members of the spinel group, commercially, is **chromite**, since it is the source of chromium and the compounds of that metal which are used as pigments. Chromite is widely distributed, and always in olivine rocks or in serpentine, especially the latter ; it is one of the heaviest (G = 4·5), and at the same time one of the softest

(H = 5½) of the spinel group; it may be recognised among other black minerals which possess submetallic lustre, and are devoid of cleavage, by the conspicuous reactions for chromium in beads of borax or microcosmic salt; but these may be largely masked by the iron reactions while the bead is hot. Chromite is sometimes very slightly magnetic.

The dunite, or olivine rock, of the Dun Mountains in New Zealand, consists entirely of olivine and a black granular mineral containing—

Cr_2O_3	Al_2O_3	FeO	MgO
56·54	12·13	18·01	14·08

intermediate in composition between picotite and chromite; many minerals referred to chromite contain Mg and Al as well as Fe. The manganese, chromium, and iron in the various members of the spinel group are recognised by pyrognostic tests.

CHRYSOBERYL

Chrysoberyl. — Aluminate of beryllium; $BeAl_2O_4$; BeO = 19·8, Al_2O_3 = 80·2. Orthorhombic.

$$a : b : c = 0{\cdot}470 : 1 : 0{\cdot}580.$$

$$p = \{111\},\ A = \{100\},\ i = \{011\},\ m = \{110\}.$$

$$Ap\ (100) : (111) = 43^\circ\ 8',\ pp\ (111) : (1\bar{1}1) = 40^\circ\ 7',\ ii\ (011) : (01\bar{1}) = 60^\circ\ 14',$$

$$mm\ (110) : (1\bar{1}0) = 50^\circ\ 21'.$$

Twinned on (031). Cleavage {010} and {011}, imperfect. Brittle. Fracture, conchoidal. H = 8½; G = 3·7. Yellowish-green. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1{\cdot}75$. Birefringence, positive; $\gamma - \alpha = 0{\cdot}009$. Axial plane (010). Acute bisectrix perpendicular to (001); $2E = 84^\circ\ 43'$; $\rho > v$. Pleochroic. Infusible. Insoluble in acids.

With the above description compare crystals from **Ceylon**.

Chrysoberyl is a rare mineral, and is chiefly known as a gemstone, rolled crystals from the alluvial deposits of Ceylon being used for this purpose; it is interesting on account of the twinning and the close relation which it bears to olivine. The mineral shows no resemblance to the spinel group, to which it is strictly analogous in chemical composition. Both the dark green crystals from the Urals, known as "alexandrite," and some of the yellowish-green stones from Ceylon, are beautiful examples of pseudo-hexagonal twinning similar to that of aragonite (Figs. 247, 248). Three interpenetrating crystals are united into a hexagonal plate with bevelled edges. The axes of chrysoberyl have been so chosen that the front of the plate (Fig. 519) is the face A, common to the three individuals, and this face is in each striated parallel to its intersection with (010); *i.e.* vertically in the central crystal of Fig. 519, which

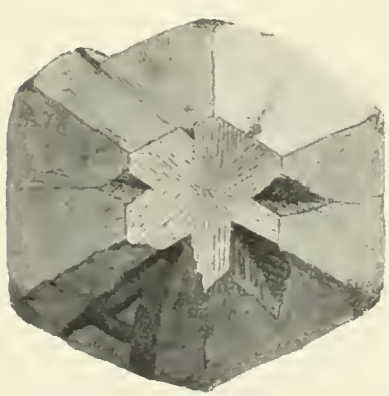

Fig. 519. — Chrysoberyl (Alexandrite) from Perm (Russia).

is in the normal position. The bevelling planes are p {111}, and the outline of the plate is formed by i {011}.

In the corresponding twin of aragonite two adjacent crystals are generally united along a surface which is nearly perpendicular to the twin plane; if the chrysoberyl twin is of the same sort, the twinning is upon the planes i {011}; but the chrysoberyl crystals may equally well be explained as due to twinning upon faces of {031} nearly perpendicular to i, in which case the twin plane is also the well-defined face of union marked by the re-entrant angles on the edges and by the striæ at the centre of the plate; the angle $(0\bar{3}1):(011)$ is 90° 14′, so that only very accurate measurements could decide between these two possible explanations. If i (011) be twin plane, then a pair of adjacent faces p, since they lie between i and A, both of which are common to two adjacent individuals, must fall into the same plane, as in the similar twins of cerussite (Fig. 553, p. 408); if $(0\bar{3}1)$ be plane of twinning and composition, two adjacent faces p will make a small re-entrant angle of 18′; the evidence is in favour of the latter, although {031} is not a form which is found as crystal faces on chrysoberyl.

Both in shape and twinning the mineral closely resembles olivine; both minerals have a pseudo-hexagonal zone ($b:c=1:0{\cdot}580=\sqrt{3}:1$).

Olivine, Mg_2SiO_4	$a:b:c=0{\cdot}465:1:0{\cdot}586$	$ii=60°\ 47'$
Chrysoberyl, Al_2BeO_4	$0{\cdot}470:1:0{\cdot}580$	$60°\ 14'$

This must be regarded as another instance of the "isomorphism" between dissimilar compounds which resemble one another in the numbers of their atoms, of which wurtzite-zincite and hæmatite-ilmenite have already been quoted as examples.

Some of the Ceylonese stones show a beautiful chatoyance, and are much prized as gems; the most remarkable are those known as "cat's-eye"; owing to the wavy opalescence which it exhibits, this variety has also received the name of cymophane (Κῦμα, a wave). The property may be due to fine tubular cavities parallel to the basal plane. This, the true cat's-eye, must not be confused with the quartz cat's-eye mentioned on p. 377. The pleochroism is well marked, the colours being red, yellow, and green for rays vibrating along the axes a b c respectively.

The deep green alexandrite appears red by transmitted light, and generally also by candle light. The light green chrysoberyl not only resembles olivine, but is often called chrysolite by the jewellers; it may be distinguished from olivine by its superior hardness and density. Chrysolite (olivine) floats in a mixture of methylene iodide with iodine and iodoform (of sp. gr. 3·6); quartz cat's-eye floats in methylene iodide; chrysoberyl sinks in both.

SECTION XIII

THE BORATES

Boracite.—Borate and chloride of magnesium; $Mg_7B_{16}Cl_2O_{30}$; MgO = 31·4, Cl = 7·9, B_2O_3 = 62·5. Pseudo-cubic; symmetry, ditesseral polar. Common form, cube with tetrahedron.

$$A = \{100\},\ d = \{110\},\ o = \{111\},\ \omega = \{1\bar{1}\bar{1}\},\ n = \{2\bar{1}\bar{1}\}.$$

Cleavage $\{111\}$, imperfect. Brittle. Fracture, conchoidal. H = 7; G = 3. Colourless. Streak, white. Lustre, vitreous. Translucent. Birefringent; $\beta = 1{\cdot}667$; $\gamma - \alpha = 0{\cdot}011$; $2V = 90^\circ$ about. Intumesces and fuses. Soluble in hydrochloric acid. Markedly pyro-electric.

The above description applies to crystals from **Stassfurt** (Prussia).

Boracite is a comparatively rare mineral found either in massive nodules or isolated crystals in the salt and gypsum deposits of Stassfurt. The massive mineral is a compact white substance, softer than the

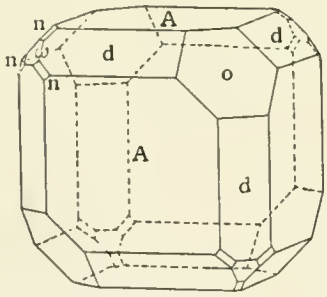

Fig. 520.—Boracite, A $\{100\}$, d $\{110\}$, o $\{111\}$, ω $\{1\bar{1}\bar{1}\}$, n $\{2\bar{1}\bar{1}\}$.

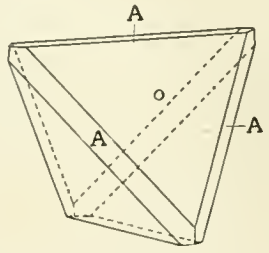

Fig. 521.—Boracite, o $\{111\}$, A $\{100\}$.

crystals, sometimes granular or earthy, and variously tinted by impurities which give it a green, yellow, or red colour.

Very perfect isolated crystals are found embedded in carnallite at Stassfurt, and in gypsum and anhydrite at Lüneburg near Hanover.

These crystals are from the theoretical point of view one of the most interesting of minerals. At first sight they are perfect cubic crystals displaying marked polar ditesseral symmetry. The ordinary combination resembles that of cube with octahedron and dodecahedron, but it can generally be observed that the faces of one tetrahedron are large, those of the other small; one is bright, the other dull; or some-

times four corners of the cube are truncated by the tetrahedron {111} alone, while the remaining four corners carry the form {2$\bar{1}$1} (Fig. 520). At Lüneburg beautiful little crystals of a bluish tint are found which are simple tetrahedra, or tetrahedra with their edges truncated by the cube (Fig. 521).

The pyro-electric character has attracted attention since the time of Haüy, who found in 1791 that a cube when heated becomes positively electrified upon four of its corners and negatively upon the remaining four. These differences are very easily shown by Kundt's method of dusting a crystal, after heating, with a mixture of red lead and sulphur, as described on p. 115; the four *o* corners of the combination of Fig. 520 become covered with red lead during cooling, the remainder (ω) with yellow sulphur.

So far there is nothing contradictory of cubic symmetry; but it has also been known since the time of Brewster that the mineral is birefringent. A transparent crystal of boracite examined under the microscope transmits light in patches between crossed nicols, and sometimes appears to have a fibrous or lamellar structure; if sufficiently thin sections be used, they are seen to consist in reality of differently orientated portions of a material which is biaxial with a large axial angle. For example, a thin slice cut parallel to one of the cube faces shows a more or less distinct division into four fields along the diagonals of the face; each field exhibits an optic axis (belonging to a biaxial crystal) emerging nearly normal to the cube face; twin lamellations and the interposition of patches differently orientated are also to be seen. The structure appears to differ for the different cube faces of one crystal, and differs also with the distance from the surface at which the section is cut. The structure has been the subject of numerous investigations and much discussion. According to Mallard, whose opinion is now generally accepted, a crystal of boracite is made up in the following way: take a rhombic dodecahedron and imagine it to be constructed of twelve pyramids, each having a dodecahedron face for base and its apex at the centre of the crystal; each of these will then be one of the twelve orthorhombic (or monoclinic?) individuals which go to form a boracite crystal; the axial plane of each crystal will be parallel to the longer diagonal of the rhombic face, and a bisectrix perpendicular to the face; the true axial angle being about 90°, one optic axis will be perpendicular to each cube face. Hence, also, no distinction can be made in this mineral between acute and obtuse bisectrix. The interpenetrating constituent crystals meet in irregular boundaries.

If the section be heated the birefringence of the different portions changes, as is shown by change in the vivid interference tints, and their boundaries move and often take up different positions when the section is allowed to cool. Mallard made the very interesting discovery that at a temperature of 265° all these optical differences suddenly disappear; the crystal becomes isotropic, and is dark between crossed nicols; on cooling, however, "optical anomalies," complexity of structure, and twin lamellation again make their appearance.

Some authors suppose that boracite originally crystallised at a high temperature as a cubic mineral, and that subsequent contraction has developed internal strains which account for the birefringence; it is not a sufficient answer to this hypothesis to point to the fact that boracite is often found enclosed in gypsum, a hydrated mineral which could not be formed at a high temperature except under great pressure, for the gypsum itself may be only a hydration-product of anhydrite.

The regular and constant characters of the boracite substance make it difficult to accept the hypothesis of internal strain as a sufficient explanation; each portion of a boracite crystal consists of the same material, having a definite refraction, birefringence, and axial angle; *i.e.*, consists of a definite mineral; the various portions differ only in their orientation.

The sub-individuals of which a boracite crystal is composed appear to be united by twinning upon planes parallel to the dodecahedron faces of the pseudo-cubic crystal.

The disappearance of birefringence at 265° must be explained by the supposition that boracite is dimorphous, and that the truly cubic form is stable above this temperature; but that at lower temperatures it is converted into a pseudo-cubic modification capable of simulating a cube by twinning.

It is very remarkable that the pyro-electric character disappears above 265°; the observations of Mack showed that the pyro-electric property is mainly developed along certain lines which traverse the surface of the crystal, and that these lines are precisely the lines of contact of the twelve sub-individuals whose existence is indicated by the optical properties.

Borax.—Hydrated borate of sodium; $Na_2B_4O_7 . 10H_2O$; $Na_2O = 16{\cdot}23$, $B_2O_3 = 36{\cdot}65$, $H_2O = 47{\cdot}12$. Monoclinic.

$$a : b : c = 1{\cdot}100 : 1 : 0{\cdot}563. \quad \beta = 73^\circ\ 25'.$$

Common form, combination of—

$$A = \{100\},\ m = \{110\},\ C = \{001\},\ z = \{22\bar{1}\},\ o = \{11\bar{1}\}.$$

$$AC\ (100) : (001) = 73^\circ 25',\ Am\ (100) : (110) = 46^\circ\ 30',\ Cm\ (001) : (110) = 78^\circ\ 40',$$

$$Co\ (001) : (11\bar{1}) = 40^\circ\ 30',\ Cz\ (001) : (22\bar{1}) = 64^\circ\ 7'.$$

Cleavage $\{100\}$, perfect, $\{110\}$ good. Brittle. Fracture, conchoidal. $H = 2$ to $2\frac{1}{2}$; $G = 1{\cdot}7$. Colourless. Streak, white. Lustre, vitreous. Transparent; $\beta = 1{\cdot}47$. Birefringence, negative; $\gamma - \alpha = 0{\cdot}004$. Axial plane (for Na) inclined at 71° 35′ to the normal of C and 35° to the normal of A. Acute bisectrix perpendicular to (010); $2E = 59^\circ\ 23'$. Marked crossed dispersion; $\rho > v$. Taste, sweet, alkaline. Intumesces and fuses. Soluble in water.

With the above description compare crystals from **Thibet**.

A considerable number of borates occur in Nature and are interesting on account of their economic importance, being employed for the manufacture of boric acid and borax. Of these compounds **borax** is the most important; it has been for a long time obtained from the salt lakes of Thibet, the waters of which contain borax in solution, and is

now largely worked at the salt lakes of California. In the neighbourhood of the borax lakes at both these localities large crystals of the mineral are found among the shore deposits; these have the same habit and other characters as crystals deposited from aqueous solution in the laboratory, and the characters are easily observed in the artificial crystals.

A noteworthy feature of borax is its striking crossed dispersion. The obtuse bisectrix for red light is inclined at 2° to that for blue light, and the dispersion is very easily seen in the interference figure, which, moreover, is easily brought within the field of view of the microscope, since the axial angle in air is not more than 60°; in examining this figure it must be remembered that not only are the axial planes crossed, but also the angle between the optic axes in air is $1\frac{1}{2}°$ greater for red than for blue light. The axial plane for red is inclined to the vertical at a larger angle than that for blue.

An important character of borax, and one which gives it great value, is its antiseptic property or power of arresting decay; it is largely used for the preservation of meat, fish, etc.

Massive borax is a white earthy material, but often coloured by impurities; it is known as "tincal."

The most beautiful mineral among the borates is **colemanite** $HCa(BO_2)_3 . 2H_2O$, discovered in 1882-83 in California; this occurs in lustrous, colourless, transparent crystals resembling calcite, except that the lustre is inclined to adamantine; the mineral is monoclinic and has a perfect cleavage parallel to {010}. The crystals, up to two or three inches in length, occur in geodes in a compact white massive colemanite. A massive white borate occurring in nodules with gypsum, which is worked at Panderma on the Sea of Marmora (**pandermite**), and a similar material (priceite) found in steatite in Oregon, have very nearly the composition of colemanite.

SECTION XIV

THE CARBONATES

THE CALCITE GROUP

Calcite	$CaCO_3$
Dolomite (Bitterspath)	$CaMg(CO_3)_2$
Magnesite	$MgCO_3$
Chalybite (Siderite, Braunspath) . .	$FeCO_3$
Calamine (Galmei, Zinkspath) . . .	$ZnCO_3$
Rhodochrosite (Dialogite, Manganspath) .	$MnCO_3$.

Calcite.—Carbonate of calcium ; $CaCO_3$; $CaO = 56$, $CO_2 = 44$. Hexagonal ; symmetry, dihexagonal alternating.

$$a : c : 1 : 0{\cdot}854 \; ; \; o\mathrm{R} = (111) : (100) = 44^\circ \; 37'.$$

$$\mathrm{R} = \{100\}, \; a = \{10\bar{1}\}, \; m = \{2\bar{1}\bar{1}\}, \; e = \{110\}, \; f = \{11\bar{1}\}, \; o = \{111\},$$
$$v = \{20\bar{1}\}, \; t = \{310\}, \; w = \{410\}.$$

RR $(100) : (010) = 74^\circ \; 55'$, *ee* $(110) : (101) = 45^\circ \; 3'$, *ff* $(11\bar{1}) : (1\bar{1}1) = 101^\circ \; 9'$, *vv* $(20\bar{1}) : (2\bar{1}0) = 35^\circ \; 36'$, *vv* $(20\bar{1}) : (02\bar{1}) = 75^\circ \; 22'$, *v*R $(20\bar{1}) : (100) = 19^\circ \; 2'$, $tt = (103) : (301) = 41^\circ \; 55'$, $ww = (104) : (401) = 49^\circ \; 23'$.

Twinned on *o* (111), *e* (110), R (100), *f* $(1\bar{1}1)$. Cleavage R, perfect. Brittle. Fracture, conchoidal. H = 3; G = 2·72. Colourless. Streak, white. Lustre, vitreous. Transparent ; $\omega = 1{\cdot}658$. Birefringence very strong, negative ; $\omega - \epsilon = 0{\cdot}172$. Infusible. Soluble, with effervescence, in acids.

With the above description compare crystals from **Egremont** (Cumberland).

Calcite (*Germ.* Kalkspath, *Fr.* Chaux carbonatée) is, with the exception of quartz, the most common of all minerals ; in most places whither calcareous solutions have penetrated, calcite has been deposited, so that, like quartz, it is a very common occupant of veins. In the form of limestone and marble it occurs massive in enormous quantities both as original deposits and as a metamorphic mineral ; as the result of the decomposition of calcium-magnesium silicates in the igneous rocks, calcite crystallises in their cavities and amygdules ; as chalk it is one of the most widely distributed minerals of organic origin.

Like quartz, again, it is found in the most perfect and beautiful crystals, and has been the subject of as much study on the part of physicists. The strong double refraction and perfect cleavage attracted

the attention of Erasmus Bartholinus (1670), at the exact time when Steno was establishing the constancy of crystal angles on quartz. Bartholinus' book, *Experimenta Crystalli Islandici*, contains a very full study of the cleavage form and the birefringence of the enormous clear crystals which had then been recently discovered in Iceland. These observations, extended by Huygens in 1690, led to the discovery of the laws of double refraction which were developed by the latter. Numerous careful and elaborate observations have since that date been made upon Iceland spar with the object of verifying or disproving Huygens' theory of double refraction. Again, Iceland spar enabled Malus (1808) to discover the polarisation of light, and as the material of the nicol prism and the dichroscope, it has acquired great value for optical researches of all sorts.

The varieties of crystalline form of calcite exceed those of all other minerals, and have been more exhaustively studied than any except, perhaps, those of quartz. Count Bournon's treatise on calcite, published in 1808, contains the description of 56 distinct forms, and up to the present time more than 200 have been recorded. The cleavage angle RR = 74° 55′ (Fig. 522) was correctly measured by Wollaston by means

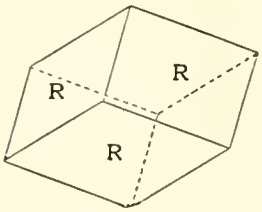

Fig. 522.—Calcite, R {100}.

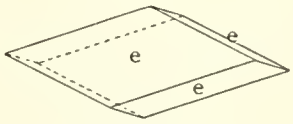

Fig. 523.—Calcite, *e* {101}.

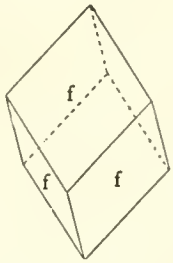

Fig. 524.—Calcite, *f* {1$\bar{1}$1}.

of his newly invented reflection goniometer in 1812; Huygens had determined this angle as 75°; while Haüy, supposing that the two diagonals of the rhombohedron face must have the simple ratio $\sqrt{3} : \sqrt{2}$, gave the angle as 75° 31′ 20″, in accordance with this supposition.

Four distinct habits of calcite may be recognised: rhombohedral, prismatic, scalenohedral and tabular. The cleavage rhombohedron R {100} (Fig. 522) is rather rare as a simple form, but occurs, for example, in fissures of a gray limestone at Poretta near Bologna. The obtuse rhombohedron *e* {110} (Fig. 523) which truncates the edges of R is quite common; for example, in the lead mines of England. The acute rhombohedron *f* {111} (Fig. 524), whose edges are truncated by R, is also rare, but is the usual form in the sandy calcite or "Fontainebleau sandstone" mentioned on p. 215, and in a similar arenaceous calcite from Vienna.

The common hexagonal prism is *m* {2$\bar{1}\bar{1}$}, which is easily distinguished from the rarer hexagonal prism *a* {10$\bar{1}$} by the fact that the cleavage R removes the edges from the former when combined with the basal pinakoid (*cf.* Fig. 15, p. 14), and the corners from the latter. This prism is either terminated by the basal pinakoid {111} (Fig. 13, p. 14) or

by the rhombohedron e (Fig. 525). Sometimes e has its edges truncated by the prism a (Fig. 526).

The common scalenohedron is $r\{20\bar{1}\}$, which is of very frequent occurrence as a simple form, and crystals of this form are known as "dog-

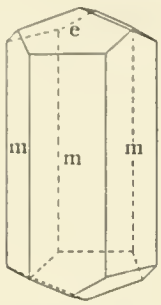

Fig. 525.—Calcite, $m\{21\bar{1}\}$, $e\{101\}$.

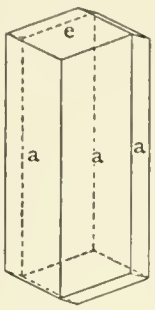

Fig. 526. — Calcite, $a\{10\bar{1}\}$, $e\{101\}$.

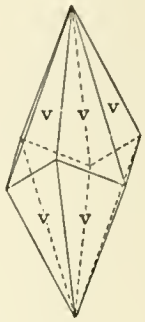

Fig. 527.—Calcite, $v\{2\bar{1}0\}$.

tooth spar" (Fig. 527). This form is usually striated parallel to its lateral edges (intersections with $\{100\}$ or $\{10\bar{1}\}$).

Tabular crystals are usually the combination mo of Fig. 13, p. 14, flattened so that m is quite small; sometimes, and especially in crystals filling thin cavities, they are a combination of the pinakoid o with R.

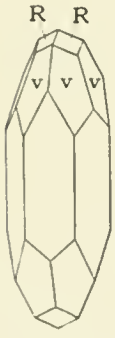

Fig. 528. — Calcite, $\{21\bar{1}\}$, $e\{210\}$. R $\{100\}$.

All the above-mentioned forms are very common in combinations, of which there is an endless variety. However complicated these may be, they may usually be deciphered by noting the position of the cleavage rhombohedron R, whose glittering facets can always, owing to the fragility of the mineral, be traced on some of the edges or corners. R meets r in edges parallel to the lateral edges of the scalenohedron itself; truncates the edge of f; replaces the corners of e; and meets m in horizontal edges.

The scalenohedral combination of Fig. 528 is a very common type of dog-tooth spar in Derbyshire, in the Harz, and elsewhere.

The rhombohedron R is the predominant form in crystals of "Iceland spar," which are sometimes found of enormous size; these crystals are dull on the surface and have a rounded appearance owing to the bevelment of the terminal edges by w, and of the lateral edges by v (Fig. 529).

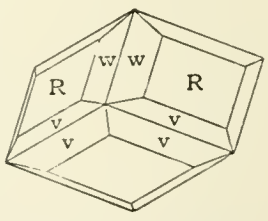

Fig. 529.—Calcite, R $\{100\}$, $e\{210\}$, $w\{410\}$.

The relations between the various forms mentioned above can be traced on the projection, Fig. 543.

Some of the most brilliant crystals are those from the copper mines of Lake Superior, from the iron mines of Cumberland, and from the Harz Mountains.

The faces on the best crystals are all smooth and bright, but there

is often a tendency to striation along the edges of the predominant zone [$eRva$], by which faces belonging to this zone may be recognised; e in particular is striated parallel to its intersection with R.

Among other combinations found on calcite are acute rhombohedra like that shown in chalybite, Fig. 546, p. 403 (*cf.* Fig. 173, p. 70).

Twinning.—Four well-defined laws are distinguished :—

1. Twin plane (111).—Two crystals are usually united by juxtaposition along the twin plane; in the scalenohedron v this introduces an

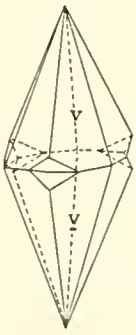

Fig. 530.—Calcite, v $\{2\bar{1}0\}$, twinned on (111).

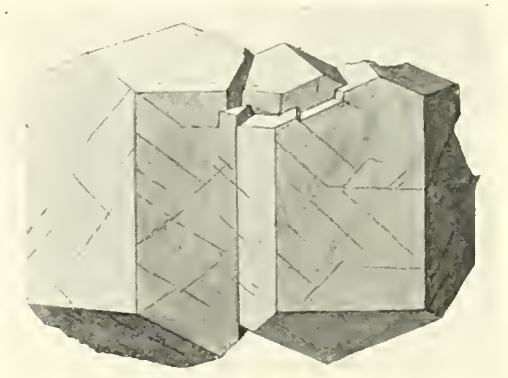

Fig. 531.—Calcite, $\{2\bar{1}\bar{1}\}$, $\{101\}$, twinned on (111) or axis [111].

equatorial plane of symmetry indicated by re-entrant angles round the middle of the crystal (Fig. 530), and this type is common among the Derbyshire crystals. But the two individuals often overlap. In crystals of prismatic habit this twinning will be shown by the occurrence of the same forms opposite to one another at the two ends of the crystals instead of in alternate positions. The twinning may equally well be described

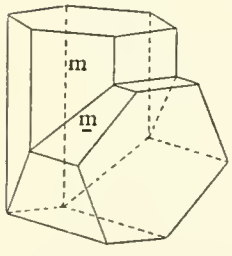

Fig. 532.—Calcite, $\{2\bar{1}\bar{1}\}$, $\{111\}$, twinned on (010).

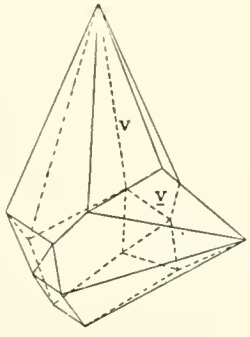

Fig. 533. — Calcite, $\{20\bar{1}\}$, twinned on (010).

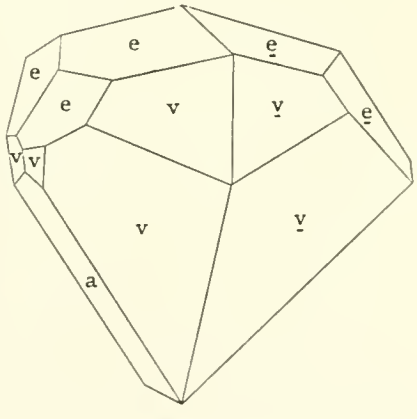

Fig. 534.—Calcite, $\{201\}$, $\{110\}$, twinned on (010).

as due to hemitropy about the vertical axis. Fig. 531 represents a twin (combination *me*) in which the two individuals are juxtaposed in reverse position and unite not along (111) but along a prism face. Fig. 540 shows the manner in which this twinning is betrayed by the cleavage.

(2) Twin plane (100).—Two crystals thus twinned have their principal axes nearly at right angles to each other; the angles are actually 89° 14′ and 90° 46′, since $oR = 44° 37'$. This mode of twinning is common both in crystals of prismatic habit (Fig. 532) and in scalenohedral crystals (Fig. 533). It can always be easily identified by the consideration that the twin plane is a cleavage plane, so that one cleavage, and only one, is parallel in the two individuals. When the crystals are of scalenohedral habit they usually meet by extension of two pairs of the faces r, so as to fill up the angle between the two individuals, and give rise to curious butterfly- or heart-shaped doublets (Fig. 534). These so-called "butterfly twins" were formerly found at Eyam in Derbyshire and recently at Egremont in Cumberland.

3. Twin plane (110).—Here, since $oe = 26° 15'$, the two individuals meet at angles of 52° 30′ and 127° 30′; although this law is the most usual of the four, juxtaposed twins united along the twin plane, and meeting at an angle of 127° 30′, are not very common. Fig. 535 represents a twin of this sort, recently found in abundance at Guanaxuato in Mexico, in which again there is a remarkable enlargement of two pairs of faces of the scalenohedron r, giving the doublet a very mis-shapen appearance. Composition perpendicular to the twin plane is far more common; from the side of one crystal a smaller crystal is often seen to emerge at an angle of $52\frac{1}{2}°$, and to be so placed that a pair of its cleavages reflect light simultaneously with a pair of cleavages of the larger crystal. The two individuals are then united in such a way that the twin plane e, which would truncate the edge of this pair of cleavages in one crystal, is parallel to the corresponding face on the other. More commonly still this twin law reveals itself by the existence of twin lamellæ parallel to e, and these appear to be often of secondary origin; the artificial twinning of calcite by gliding along e has been described on p. 95. The effect of pressure is to produce such lamellæ in any crystal of calcite, and much calcite lining fissures or cavities in other rocks has been probably subjected to pressure, and is traversed by such lamellæ. In thin sections made for the microscope they are so characteristic as to serve for the identification of calcite. Fig. 542 represents a section of granular limestone, in which each grain shows the characteristic lamellæ of secondary twinning parallel to e.

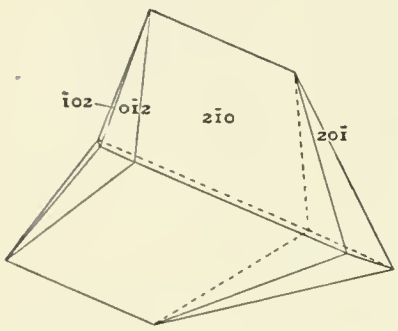

Fig. 535.—Calcite, $\{2\bar{1}0\}$, twinned on (110).

4. Twin plane $(11\bar{1})$.—The two individuals here intersect at angles of 53° 46′ and 126° 14′, since the angle $of = 63° 7'$. A twin, like Fig. 536, in which f is also the plane of composition, will therefore very closely resemble a twin of the last class, in which composition is perpendicular to the twin plane e, for in each case the two individuals are inclined at about 53°. In the present law, however, cleavage planes are no longer parallel in the two individuals, since f does not truncate RR. It will be

seen from Fig. 536, and from the projection, Fig. 543, that the plane of

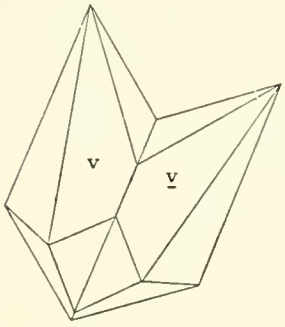

Fig. 536.—Calcite, $\{20\bar{1}\}$, twinned on $(\bar{1}11)$.

Fig. 537.—Calcite, $\{2\bar{1}\bar{1}\}$, $\{110\}$, twinned on (111) (Egremont) (Brit. Mus.).

composition f truncates the acute edge of the scalenohedron v $(20\bar{1} + 02\bar{1} = 11\bar{1})$. Hence in Fig. 536 two obtuse edges of the scalenohedron face one another in the acute angle between the individuals; in

Fig. 538.—Calcite from Guanaxuato (British Museum).

a twin according to the third law, two acute edges would face one another.

All the above four laws are illustrated by the beautiful crystals recently found at Egremont in Cumberland.

Fig. 538 represents a typical group of scalenohedral calcite from

Guanaxuato. Fig. 539 is a group from Wheal Wrey near Liskeard,

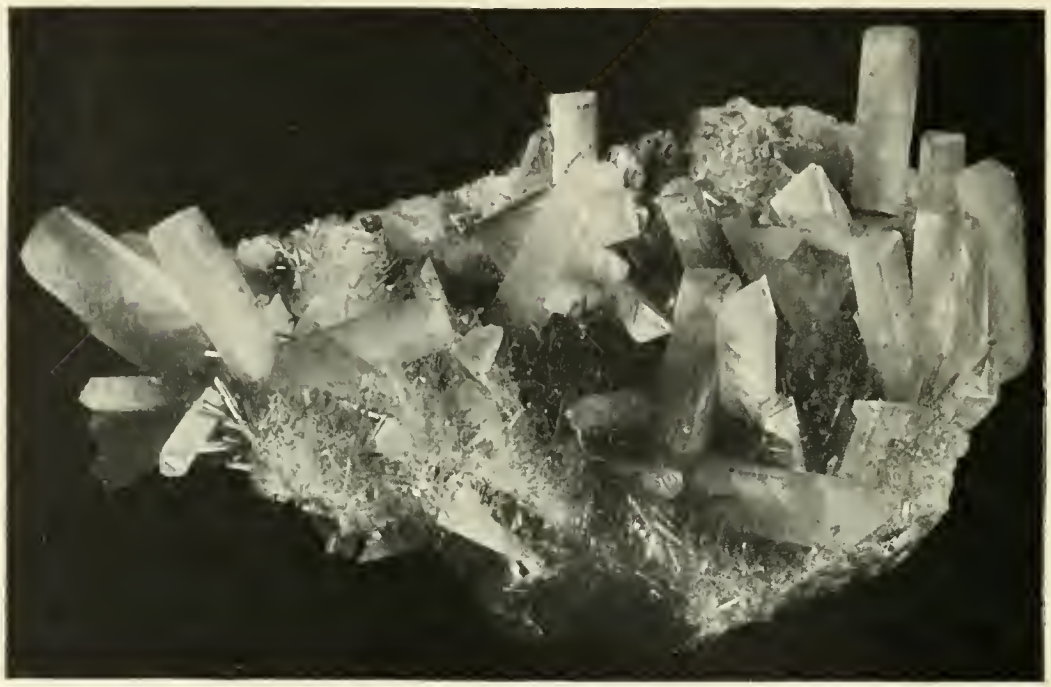

Fig. 539.—Calcite from Wheal Wrey (Liskeard) (British Museum).

where specimens of great beauty were formerly found; the crystals resemble trigonal prisms but are really very acute rhombohedra, mostly

Fig. 540.—Calcite, cleavage from crystal twinned on (111) (British Museum).

twinned on R, like Fig. 532. Fig. 541 is a beautiful group of prisms from Egremont—a locality which has furnished so many varieties.

The hexagonal bipyramid of Fig. 176, p. 71, the particular case of a scalenohedron whose faces are equally inclined to two adjacent planes of symmetry, is extremely rare. Crystals showing faces of such forms have been found at Rhisnes in Belgium and Visby in Sweden, with the indices {917}.

Special names have been given to some of the more peculiar habits of calcite. "Dog-tooth spar" (Fig. 527) and "nail-head spar" (Fig. 216, p. 85), have been already mentioned; "slate spar," or "schieferspath," is the thin tabular variety due to predominance of the basal pinakoid; the plates are sometimes as thin as paper, and often grouped parallel to one

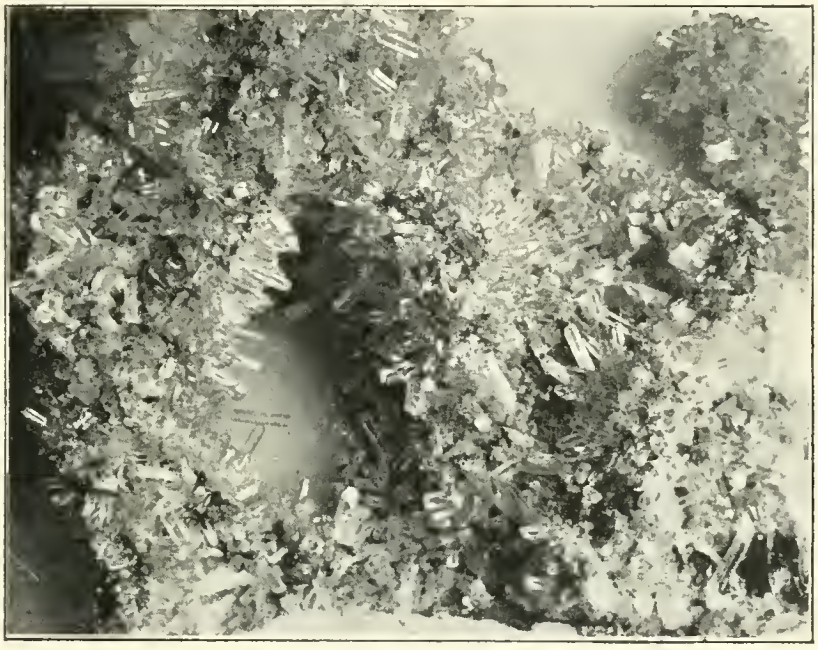

Fig. 541.—Calcite from Egremont (British Museum).

another; this platy structure may give rise to an apparent cleavage or parting parallel to {111}.

The conchoidal fracture mentioned on p. 257 (Fig. 407) is difficult to obtain owing to the facility of the R cleavage; there is often also a parting parallel to *e* in crystals which have undergone pressure, owing to gliding and secondary twinning along that plane.

A very remarkable feature due to this twinning is presented by some calcite; when a candle flame is viewed through certain crystals or cleavage fragments it appears as a radiating star of light; this effect is known as asterism; it is also exhibited by some mica and labradorite, and in those minerals is due to minute enclosures arranged in certain definite directions. The asterism of calcite is due to systems of minute hollow tubes which seem to have been produced where the gliding surfaces *e* intersect one another; these are parallel to each other in three directions.

The use of calcite as the material of nicol prisms is made possible by

the fact that of its two principal indices, ω (1·658) is much greater, and ϵ (1·486) is very slightly less than the index of Canada balsam (1·536); owing to the same cause a microscopic section of calcite mounted in Canada balsam, when rotated on the stage above the polariser (without using the analyser), appears in one position to have a high relief, and

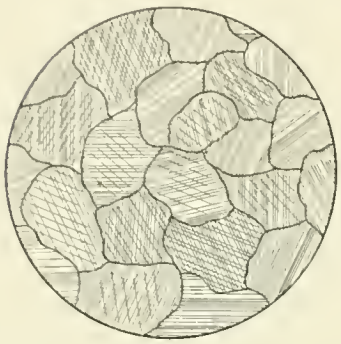

Fig. 542.—Section showing twin lamellæ {110} of Calcite.

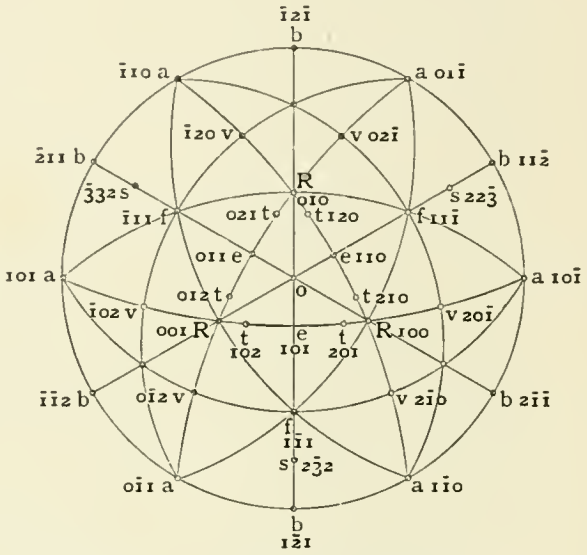

Fig. 543.—Projection of Common Forms of Calcite.

when turned through a right angle to be almost invisible, since in one position the transmitted light consists of the ordinary and in the other position of the extraordinary rays. This effect, which is quite different from pleochroism, is sufficient to identify calcite in thin sections.

Some Noteworthy Localities:

Eskifjördhr (Iceland).—This is the locality of the famous "Iceland spar." A cavity in the dolerite about 36 feet by 15 feet in area and 10 feet high, was filled with clear crystallised calcite; the crystals are of two habits, either rhombohedra {100} with bevelled edges {410}, {20$\bar{1}$}, like Fig. 529, or scalenohedra {20$\bar{1}$} terminated by {410}, {100}.

The crystals are dull and somewhat corroded on the surface and often coated with crystals of stilbite. Some of the calcite crystals were of enormous size; one in the British Museum is about $2\frac{1}{2}$ feet by $1\frac{1}{2}$ feet.

Derbyshire.—In the veins of the Carboniferous limestone fine crystals of scalenohedral habit used to be found in the neighbourhood of **Matlock**, **Eyam**, etc., often associated with galena and fluor. Among these the (111) twin, like Fig. 530, and the heart-shaped (100) twins, like Fig. 534, are especially noteworthy.

North of England.—In the lead mines of **Alston** (Cumberland), and of **Weardale** (Durham), in the iron mines of **Furness** (Lancashire), and **Egremont** (Cumberland), fine specimens have been found, often of prismatic habit and often scalenohedral, and generally showing faces

of e {110}, which are striated parallel to their intersections with R {100}. An acute rhombohedron {$3\bar{1}1$} may often be discerned among the forms present among north of England calcites. The crystals discovered at Egremont in 1888 were found in cavities in the Carboniferous limestone, associated with a soft earthy hæmatite and consequently very fully developed and easy to detach; they illustrate many varieties of habit and most of the twin laws. Fig. 541 is a large and beautiful group of prismatic habit, {$2\bar{1}1$} terminated by {100}, {110}, in the British Museum; other crystals are very acute rhombohedra, like Fig. 546 of chalybite; others, again, very acute scalenohedra which look like sharp hexagonal bipyramids. Among the twins are large heart-shaped twins on (100), like those from Eyam in Derbyshire (Fig. 534), and also the rare twin on f ($11\bar{1}$), shown in Fig. 537.

Andreasberg (Harz Mountains).—A great variety of beautiful specimens have been found in the mines of this district in the metalliferous veins in clay-slate, where the calcite accompanies ores of lead, silver, and arsenic, together with zeolites. Crystals of prismatic and tabular habits are common, especially combinations of m {$2\bar{1}\bar{1}$} and e {110}. The basal pinakoid {111} is usually dull.

Joplin (Missouri).—Beautiful, clear, honey-yellow scalenohedra v {201}, terminated by R {100}, and striated faces of e {110}, have recently been found; the more acute terminal edges of v are sometimes replaced by striated and rounded faces.

Dolomite.—Carbonate of calcium and magnesium; $CaMg(CO_3)_2$; CaO = 30·4, MgO = 21·7, CO_2 = 47·9. Hexagonal; symmetry, hexagonal alternating

$$a : c = 1 : 0{\cdot}832 \; ; \; oR = (111):(100) = 43^\circ 51\tfrac{1}{2}'.$$

Common form, R {100}. RR (100) : (010) = 73° 45′.

Twinned on o (111). Cleavage {100}, perfect. Brittle. Fracture, sub-conchoidal. H = $3\frac{1}{2}$; G = 2·85. Colourless. Streak, white. Lustre, vitreous. Transparent; $\omega = 1{\cdot}682$. Birefringence very strong, negative; $\omega - \epsilon = 0{\cdot}189$. Infusible. Soluble with effervescence in warm acids.

With the above description compare crystals from **Binnenthal** (Switzerland).

Dolomite is especially interesting for two reasons: (1) because it belongs to the dioptase or hexagonal, and not to the calcite or dihexagonal, class of alternating symmetry; (2) because it is a double salt, in which calcium carbonate and magnesium carbonate are united in the proportion of one molecule of each, and not an isomorphous mixture of calcite with magnesite. The absence of planes of symmetry is proved by the etching and elasticity figures (see Figs. 267, 271, pp. 109, 112), and also by the occasional appearance of six facets on the corners of the primary rhombohedron R {100}. These, like the faces s in Fig. 187, constitute a second rhombohedron, instead of the scalenohedron of calcite, and prove that the faces R are not perpendicular to planes of symmetry.

The fact that dolomite is not an isomorphous mixture is proved by

its specific gravity (2·850) being greater than that (2·843) which would belong to a mixture of $CaCO_3$ and $MgCO_3$ in equal molecular proportions, showing that, as is usual in such cases, there has been a contraction in the union of the two carbonates.

Dolomite is very commonly twinned by hemitropy about the vertical axis of symmetry [111]; the two rhombohedra interpenetrate, as in Fig. 544. Other twin laws are also known, but are rare; among them is supplementary twinning which gives the crystal the dihexagonal symmetry of calcite. Another respect in which dolomite differs from calcite and magnesite is that e {110} is not a gliding plane or plane of secondary twinning. The lustre of dolomite is often inclined to pearly; its faces are very frequently curved. Fig. 545 represents a specimen of pearly

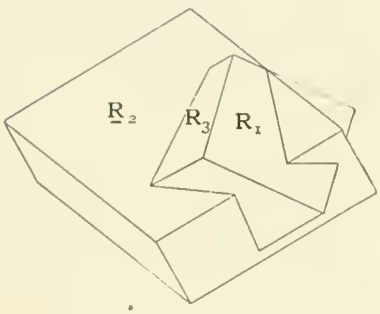

Fig. 544.—Dolomite, R {100}, twinned on axis [111].

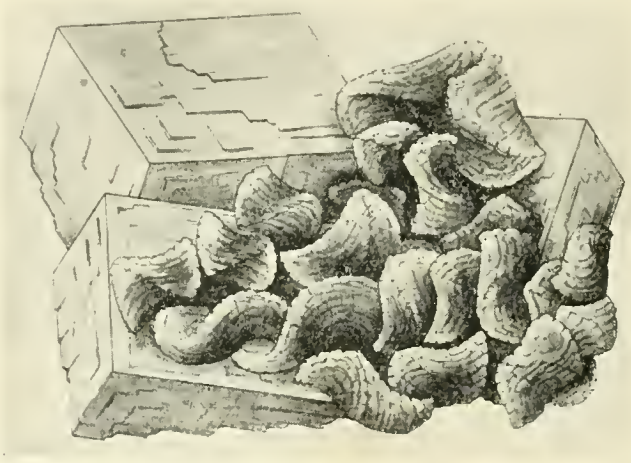

Fig. 545.—Dolomite on Fluor, from Liskeard.

dolomite upon cubes of fluor spar from the Menheniot mines near Liskeard (Cornwall); the dolomite crystals are here doubly curved, so that they become saddle-shaped, and they have a characteristic scaly texture.

Massive dolomite, like limestone, is found in large beds constituting whole tracts of country (*e.g.* the magnesian limestone in North England) or mountain ranges, as in the "dolomite" region of the Tyrol; much of the latter is in reality limestone. The white crystalline dolomite of the Binnenthal in Switzerland is the source of beautifully crystallised blende, realgar, and many sulpharsenites, and the best crystals of dolomite (like Fig. 544) are found in its cavities; the massive mineral is traversed by thin threads of pyrites (see Section III. Fig. 448) in the neighbourhood of these metallic minerals. Another noteworthy occurrence of dolomite is that of *black*, acute, positive rhombohedra, like Fig. 546, found in anhydrite at Hall in the Tyrol.

Chalybite.—Carbonate of iron; $FeCO_3$; $FeO = 62{\cdot}1$, $CO_2 = 37{\cdot}9$. Hexagonal; symmetry, dihexagonal alternating.

$a : c = 1 : 0{\cdot}818$; $o\mathrm{R} = (111) : (100) = 43^\circ\ 23'$.

Common forms, R {100}, o {111}. RR (100) : (010) = 73° 0′.

Twinned on e (110). Cleavage {100}, perfect. Brittle. Fracture, subconchoidal. H = 3½; G = 3·8. Brown. Streak, white. Lustre, vitreous. Translucent; $\omega = 1{\cdot}873$. Birefringence very strong, negative; $\omega - \epsilon = 0{\cdot}241$. Fuses (4½) to black magnetic globule. Soluble with effervescence in warm acid.

With the above description compare crystals from **Neudorf** (Harz).

Chalybite is one of the common ores of iron, and is found in good crystals in many metalliferous veins, as at Freiberg, and in the Harz, and in Cornwall. Like dolomite it usually occurs in the simple rhombohedra {100}, which are comparatively rare in calcite. But the habit is very variable. Acute rhombohedra like Fig. 546 (d = {533}), with or without the basal plane, are not uncommon. Fig. 547 represents a tabular variety formerly found at Wheal Maudlin, near Lostwithiel, in Cornwall, to be seen in many collections; brown crystals with large curved faces of {111} and drusy rhombohedron and prism faces; they show a distinct zonal structure marked by hexagonal bands of different

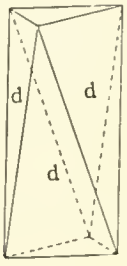

Fig. 546.—Chalybite, d {533}.

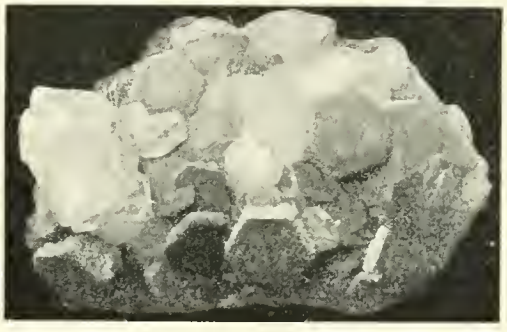

Fig. 547.—Chalybite on Quartz, from Lostwithiel (British Museum).

shades on the basal plane. The twinning of chalybite is chiefly visible as lamellæ parallel to {110}.

This mineral is sometimes not only acute in habit, like Fig. 546, but even fibrous, and, like most fibrous minerals, tends to botryoidal and globular forms. "Clay ironstone," an impure argillaceous chalybite, which in the coal measures of Staffordshire, Yorkshire, and Wales, is the most important iron ore of England, is frequently found concretionary and in globular masses; these are sometimes called "sphærosiderite."

Chalybite is liable to oxidation and hydration and passes into deep brown or black limonite. Very perfect pseudomorphs of limonite after chalybite have been found at Traversella in Piedmont; dehydration then leads to the formation of hæmatite or magnetite; some dark chalybite acts feebly on the magnetic needle.

The calcite group is perhaps the best-defined group among minerals; each member crystallises in the rhombohedral system, their common forms are very similar, they all have a perfect cleavage parallel to the faces of a rhombohedron of about 75°, and they form a large series of isomorphous mixtures.

As might be expected in compounds of the above metals, they differ widely in appearance. Calcite, dolomite, magnesite and calamine, when pure, are colourless; chalybite is gray; rhodochrosite, a delicate pink; and the isomorphous mixtures show a great variety of tints. They are easily distinguished from minerals of similar appearance which are not carbonates by their brisk effervescence with acids (dolomite, chalybite and magnesite only with warm acids), and the cleavage distinguishes them from other carbonates.

Dolomite, the mineral of less symmetrical composition, is the only one whose symmetry has been proved to belong without doubt to the dioptase type; the etching figures of magnesite and chalybite point to the possibility of their belonging to the same class. It is, of course, possible that the whole group is really hexagonal alternating, and not dihexagonal, but liable to supplementary twinning, and that in dolomite alone the usual absence of this twinning discloses the true symmetry.

Dolomite, although a double salt, appears to be isomorphous with the others and contains intermixed chalybite, calamine, and rhodochrosite; even those specimens which contain only calcium and magnesium vary much in composition owing to intermixture with calcite and magnesite.

Rhodochrosite is not often found well crystallised; beautiful pink rhombohedra {100} with iron pyrites have been found at Alicante in Colorado; this mineral also occurs in acute scalenohedra.

Calamine, which is colourless when pure, but is more usually green, blue, or brown, owing to the intermixture of other carbonates (?), is also rare in crystals, and tends, like chalybite, to botryoidal forms. Particularly remarkable are white earthy spherical concretions found in the zinc mines of Santander in Spain.

Intermixtures of all the rhombohedral carbonates are very common; the pure minerals are rare. That $CoCO_3$ belongs to the same series is proved by the presence of cobalt in some rhodochrosite and dolomite, and a red botryoidal substance found at Schneeberg in Saxony, and named **sphærocobaltite**, has the composition $CoCO_3$ and appears to consist of minute rhombohedra.

Special names have been given to many of the mixtures by Breithaupt and others: "mesitite" (the midway mineral) to the pale brown obtuse rhombohedra of Traversella, whose composition is $2MgCO_3 . FeCO_3$; "pistomesite" (the truly midway mineral) to brown crystals from Salzburg which were found to have the composition $MgCO_3 . FeCO_3$; "ankerite" to varieties approximating to $2CaCO_3 . MgCO_3 . FeCO_3$; "breunnerite" to the ferriferous magnesite from the Greiner in Tyrol. But dolomite is the only one which can be at all certainly distinguished as a double salt.

"Brown spar" is a name conveniently used for the brown ferriferous Ca-, Mg-carbonates; "pearl spar" for the paler coloured varieties with pearly lustre which usually approximate to the composition of dolomite. Both of these frequently have curved faces and form saddle-shaped crystals like Fig. 545. In these, as in chalybite and dolomite, even the cleavage surfaces are usually curved. These minerals of the calcite-

dolomite-chalybite series are common as constituents of metalliferous veins and as associates of iron ores. **Magnesite** occurs commonly as a decomposition product of the ferro-magnesian silicates; thus the white patches in serpentine consist mainly of a compact magnesite. Calamine occurs in more isolated localities, where it is worked as an important ore of zinc, *e.g.* in the zinc mines of Siberia, Aachen, Santander, etc.; in the Derbyshire mountain-limestone it occurs in pseudomorphous crystals after calcite. Blende is sometimes altered into a white earthy calamine.

The lead present in calcite from Wanlockhead, the barium and strontium present in some other calcites, and the cadmium, which sometimes imparts a yellow colour to calamine, indicate that $PbCO_3$, $BaCO_3$, $SrCO_3$, $CdCO_3$ also belong to the series of rhombohedral carbonates.

THE ARAGONITE GROUP

Aragonite	$CaCO_3$
Witherite	$BaCO_3$
Strontianite	$SrCO_3$
Cerussite (Weissbleierz)	$PbCO_3$
Bromlite (Alstonite)	$(Ba,Ca)CO_3$

Aragonite.—Carbonate of calcium; $CaCO_3$; $CaO = 56$, $CO_2 = 44$. Orthorhombic; holosymmetric (?)

$$a : b : c = 0{\cdot}623 : 1 : 0{\cdot}721.$$

$$B = \{010\},\ m = \{110\},\ C = \{001\},\ p = \{111\},\ k = \{011\}.$$

$$mm\ (110) : (1\bar{1}0) = 63^\circ\ 48',\ kk\ (011) : (0\bar{1}1) = 71^\circ\ 34'.$$

Twinned on m (110). Cleavage $\{010\}$, $\{110\}$, imperfect. Brittle. Fracture, sub-conchoidal. $H = 3\frac{1}{2}$; $G = 2{\cdot}9$. Colourless. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1{\cdot}682$, $\alpha = 1{\cdot}530$. Birefringence very strong, negative; $\gamma - \alpha = 0{\cdot}156$. Axial plane (100); acute bisectrix perpendicular to (001). $2E = 30^\circ\ 53'$; $\rho > v$. Infusible. Soluble in acids with effervescence.

With the above description compare crystals from **Bilin** (Bohemia).

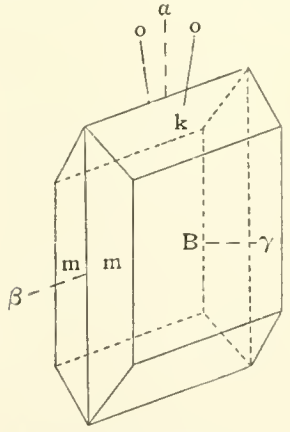

Fig. 548.—Aragonite. B $\{010\}$, m $\{110\}$, k $\{011\}$.

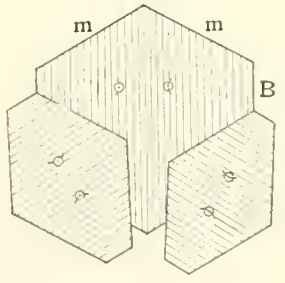

Fig. 549.—Aragonite Triplet twinned on m $\{110\}$.

Aragonite, so called after the locality in Spain where it was first found, is interesting as the earliest and best established instance of

dimorphism in the mineral kingdom, having the same composition as calcite. The crystals generally resemble hexagonal prisms, or are tabular, as in Fig. 548, when the faces B are large in comparison with *m*, and they are sometimes terminated by the basal pinakoid alone.

In several localities aragonite adopts an acute pyramidal habit due to the predominance of pyramids such as {441} or {991}, and brachydomes such as {081} and {091}. These are usually striated horizontally. Fig. 550 represents a fine specimen from Cleator in Cumberland, in the British Museum.

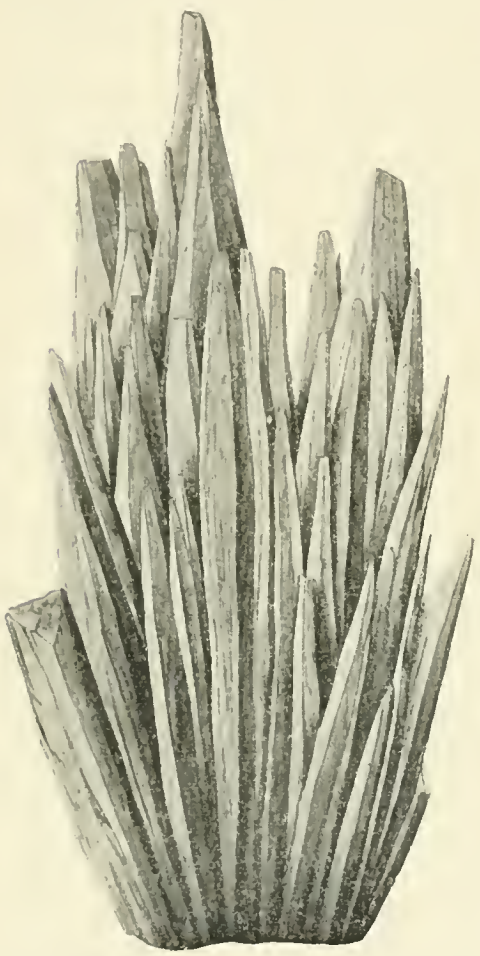

Fig. 550.—Aragonite from Cumberland (British Museum).

Simple forms are rare; some of the single crystals from Bilin present the combination of Fig. 548; more usually they are twins or triplets, as in Figs. 239-241 and 246-248. Beautiful examples like Fig. 248 have been found at Girgenti in Sicily, and at Herrengrund in Hungary. Complex crystals betray their twin nature not only by re-entrant angles on the prism faces and by the striations on C parallel to the edge CB, but also, in thin section, by the different orientation of the optic axes—as shown in Fig. 549; as the section is moved across the microscope stage these are seen to change their position. (See also p. 182.) These pseudo-hexagonal groups are usually somewhat irregular, as shown in Fig. 551, and the faces C do not fall into one plane.

The usual type of the crystals from Aragon is shown in the triplet of Fig. 248, where, since the prism angle is 63° 50′, there is a re-entrant angle of 11° 30′ on two opposite faces of the apparently hexagonal prism. In the Sicilian and Bohemian crystals the interstices shown in Fig. 246 are often filled by the intercalation of a fourth or fifth individual. Some etching experiments on aragonite indicate that the symmetry may really be polar; if this be so the apparently simple crystals are themselves supplementary twins.

Aragonite is far less common than calcite; solutions of calcium carbonate in water containing CO_2 have been found to deposit calcite when cold, whereas hot solutions deposit aragonite or a mixture of aragonite with calcite; and some of the natural occurrences are to be traced to deposition from hot solutions. It is also less stable at ordinary temperatures than calcite; crystals of aragonite have been found altered to calcite; such cases of pseudomorphism without any

chemical change are known as "paramorphs." Many concretionary, botryoidal, and stalactitic forms of carbonate of lime are usually referred to aragonite, especially such as are fibrous, since fibrous calcite is rare; such are the "pisolites," or spherical concretions (*Sprudelstein*, *Erbsenstein*), deposited from the hot springs of Carlsbad in Bohemia (see Fig. 401, p. 252), and the beautiful white coralline stalactites known as *flos-ferri*, of which the best specimens come from the iron mines of Eisenerz in Styria (see Fig. 402, p. 253). But unless the cleavage can be identified or the specific gravity ascertained with accuracy, it is not always possible to distinguish with certainty between massive calcite and aragonite.

Through a cleavage flake of calcite or any of the rhombohedral carbonates the rings surrounding the optic axis are seen at the edge of the field of view in convergent light; fragments of aragonite usually show an obtuse positive bisectrix.

Some Noteworthy Localities:

Girgenti (Sicily).—Large white, yellowish or brown prisms, twinned, and showing the characteristic striæ on the basal plane, are associated with sulphur and small prisms of celestite. This occurrence has been described under sulphur (p. 300). The crystals found at Herrengrund in Hungary are similar in habit, but are white; they occur on a granular calcite and are also associated with celestite.

Molina (Aragon, Spain).—The prisms or groups of prisms, Fig. 551, are usually brown or red in colour and very much corroded on the basal planes; they are found in a red ferruginous marl together with gypsum; small red crystals of ferruginous quartz are sometimes dispersed on the aragonite.

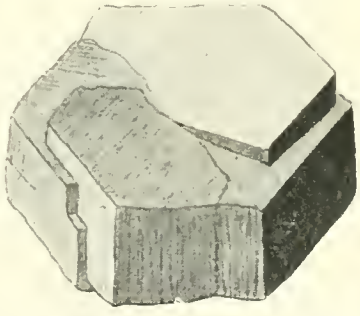

Fig. 551.—Aragonite Triplet from Aragon.

Aragonite, indistinguishable from that of Aragon, is found under the same conditions on the other side of the Pyrenees, at Bastennes in the south of France.

Horschenz (near Bilin, Bohemia).—Transparent yellowish or pale green aragonite is found as isolated crystals in a soft calcareous material which fills large cavities in an olivine basalt, or lines druses of fibrous aragonite in the same. Some of these are doubly terminated and are either single crystals of the habit of Fig. 548, or examples of the different twins and triplets described above.

Two other members of the aragonite group occur commonly in good crystals, namely cerussite and witherite.

Cerussite.—Carbonate of lead; $PbCO_3$; $PbO = 83{\cdot}5$, $CO_2 = 16{\cdot}5$. Orthorhombic; holosymmetric.

$$a : b : c = 0{\cdot}610 : 1 : 0{\cdot}723.$$

$$B = \{010\},\ m = \{110\},\ p = \{111\},\ i = \{021\}.$$

$$mm\ (110) : (1\bar{1}0) = 62^\circ\ 46',\ Bi\ (010) : (021) = 34^\circ\ 40',\ pp\ (111) : (1\bar{1}1) = 50^\circ\ 0',$$
$$pm\ (111) : (110) = 35^\circ\ 46'.$$

Twinned on (110), also on (130). Cleavage {110}, {021}, imperfect. Brittle. Fracture, conchoidal. H = 3½; G = 6·5. Colourless. Streak, white. Lustre, adamantine. Transparent; $\beta = 2{\cdot}076$, $\alpha = 1{\cdot}804$. Birefringence, strong, negative; $\gamma - \alpha = 0{\cdot}274$. Axial plane (010); acute bisectrix perpendicular to (001). $2E = 17° 8'$; $\rho > v$. Soluble in nitric acid.

With the above description compare crystals from **Mies** (Bohemia).

The aragonite group not only constitutes a series dimorphous with the calcite group, but each member of it by repeated twinning becomes pseudo-hexagonal and simulates the form of the latter.

Among these minerals **cerussite** occurs in the best crystals; its faces are often very bright and smooth, and it displays the characteristic twinning better even than aragonite. Its habit is very varied, and its forms many; most usual are crystals of pyramidal habit, like Fig. 552,

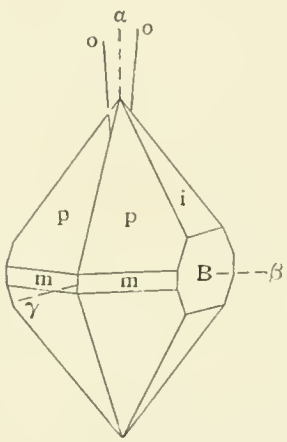

Fig. 552.—Cerussite, B {010}, *p* {111}, *m* {110}, *i* {021}.

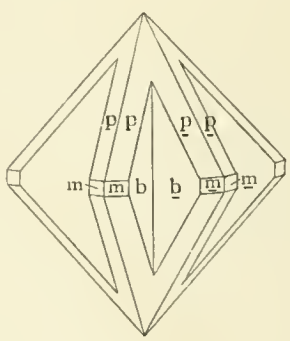

Fig. 553.—Cerussite Triplet, *b* {010}, *p* {111}, *m* {110}, twinned on *m* {110}.

or of tabular habit, like Fig. 548 of aragonite. The latter, when twinned, often assume stellar and cruciform groups, in which the spaces between the individuals are not filled in (Fig. 553). Here, composition being perpendicular to the twin plane (m, m), the adjacent pyramid faces p, p also fall into a plane and reflect light together; by this characteristic feature cerussite crystals may often be recognised.

In a pseudo-hexagonal zone, such as the prism zone of this group, where $(110) : (1\bar{1}0) = 60°$ about, the lengths of the axes as determined from the face (110) are $a : b = 1 : \sqrt{3}$, approximately; the face (130) will therefore intersect the axes with intercepts $\frac{a}{1} : \frac{b}{3}$, *i.e.* $\sqrt{3} : 1$, and must be a prism having (130) : (130) also about 60°. In such cases it is usual to find that both pseudo-hexagonal prisms may be planes of twinning. Cerussite is usually twinned on (110), but also, though rarely, on (130).

In the similar case of chrysoberyl (p. 387), the two forms have so nearly the same angle that it is almost impossible to say which is the twin plane.

In cerussite the angle of {110} is 62° 46′, and that of {130}, 57° 19′, so that it is easy to distinguish between them. Twinning on (130) has not been observed on other members of the aragonite group.

Cerussite is found not only in brilliant translucent crystals of tabular, prismatic, and pyramidal (sometimes acute) habits, but also in acicular or fibrous masses which are dead white and opaque; the best fibrous specimens were formerly found at Pentire Glaze mine, near St. Minver in Cornwall (Fig. 386, p. 246). These will hardly be recognised at first sight as cerussite, but they possess the characteristic adamantine lustre, inclining to resinous, which belongs to so many minerals containing lead.

The finest specimens of cerussite are from the Friedrichssegen mine near Ems in Nassau, and from Mies in Bohemia, where they occur in metalliferous veins upon galena and quartz. Large crystals of various colours, including green, have been found in the lead mines of Nerchinsk in Siberia. Large, white, twinned groups of arrow-head form come from the Broken-Hill silver mines in New South Wales, where they are associated with ores of copper and silver. Cerussite is one of the important ores of lead, and is found in most lead mines as a decomposition product of galena.

Witherite.—Carbonate of barium; $BaCO_3$; $BaO = 77{\cdot}7$, $CO_2 = 22{\cdot}3$. Orthorhombic; holosymmetric.

$$a : b : c = 0{\cdot}603 : 1 : 0{\cdot}730.$$

$m = \{110\}$, $B = \{010\}$. $k = \{011\}$. Common form, pseudo-hexagonal bipyramid.

Twinned on (110). Cleavage {010}, {110}, imperfect. Brittle. Fracture, uneven. $H = 3\frac{1}{2}$; $G = 4{\cdot}3$. Colourless. Streak, white. Lustre, vitreous. Translucent; $\beta = 1{\cdot}531$. Birefringence, negative, weak. Axial plane (010); acute bisectrix perpendicular to (001). $2E = 26° 30'$; $\rho > r$. Fusible (2). Soluble in hydrochloric acid.

With the above description compare crystals from **Hexham** (Northumberland).

Strontianite and **witherite** are comparatively rare minerals, but are the chief sources of strontium and barium compounds; the former is much used for fireworks and in the separation of sugar from molasses, the latter for rat poison. The element strontium was first discovered in the strontianite from Argyleshire in 1791; at Strontian the mineral occurs as fibrous green or brownish masses, rarely terminated. Acute white pyramids of strontianite, horizontally striated like those of aragonite, are found in the lead mines of Pateley Bridge in Yorkshire. Still better acute crystals have been found in veins in a calcareous marl at Hamm in Westphalia.

Strontianite closely resembles aragonite in its varieties of habit (Figs. 548 and 550 of aragonite), and its twinning, but is seldom found in well-defined crystals, usually in prisms which are vertically striated and imperfectly terminated.

We have seen that interpenetrant triplets of aragonite form pseudo-hexagonal prisms; witherite is invariably of pyramidal habit, and in a similar way forms pseudo-hexagonal bipyramids, Fig. 554. A cross-section of a witherite crystal viewed in convergent light resembles one of

aragonite (Fig. 368), and is seen to consist of sectors, having three or more different orientations. It must be remembered, however, that for witherite, as for cerussite, the plane of the optic axes is (010), whereas for aragonite it is (100). Witherite invariably occurs in these bi-pyramids.

The best specimens of witherite have been found at the Fallowfield lead mine at Hexham in Northumberland; they occur in veins traversing the carboniferous limestone, and are white hexagonal bipyramids, sometimes an inch or more in diameter, associated with galena, and often surrounded by sharp hexagonal bipyramids of bromlite (Fig. 554). The crystals are sometimes obtuse, owing to the predominance of flatter pyramids. They often have a greasy lustre on the surface, or a dull white colour owing to a superficial coating of barytes. The neighbouring lead mines of Alston Moor in Cumberland yield similar crystals. The mineral discovered and analysed by Withering in 1783 was a fibrous variety from Anglesark in Lancashire.

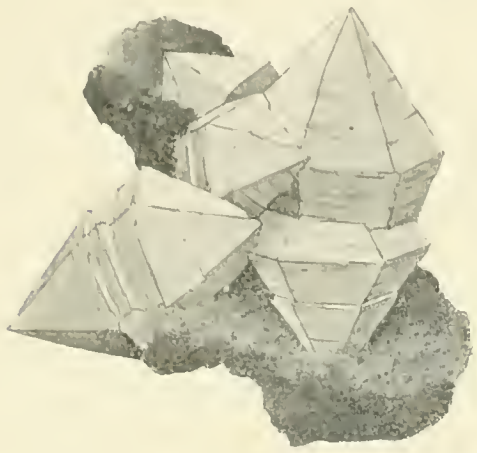

Fig. 554.—Witherite from Hexham.

Isomorphous mixtures are not so common in the aragonite as in the calcite group. Strontianite usually contains some $CaCO_3$; the aragonite from Tarnowitz in Silesia contains as much as 9 per cent of $PbCO_3$; the cerussite from Monte Poni contains 7 per cent of $ZnCO_3$; strontium is also found in some aragonite.

The mineral **bromlite** (or alstonite), mentioned above, occurs in small hexagonal bipyramids resembling witherite but sometimes of a pink tint, at Bromley Hill near Alston, and corresponds somewhat to dolomite in the calcite group; its composition sometimes corresponds to $CaCO_3 . BaCO_3$, and its specific gravity, 3·706, is higher than should correspond to a mixture of aragonite and witherite in these proportions, so that it may be a double salt; but it varies considerably in composition, and it may therefore be an isomorphous mixture of this double salt with aragonite and witherite.

RELATION BETWEEN THE CALCITE AND ARAGONITE GROUPS

From the preceding pages it is clear that the carbonates of Ca, Mg, Ba, Sr, Fe, Co, Mn, Zn, Pb, are to be regarded as isodimorphous and capable of forming isomorphous mixtures, both in their hexagonal and orthorhombic modifications; that they may also unite in molecular proportions to form double salts is probable from the evidence afforded by dolomite and bromlite; in these cases the double salt is itself isomorphous with the group. But it is interesting to find that there is a second molecular compound of barium and calcium carbonates

also represented by $BaCa(CO_3)_2$, which crystallises in the monoclinic system and cannot be referred to either group. This is the mineral **barytocalcite,** which is also found at Alston, and occurs in white translucent crystals represented in Fig. 555. The mineral in some respects resembles calcite, for there is a perfect cleavage parallel to *m* {110}, and a nearly perfect cleavage parallel to C {001}; the angles, C*m* (001) : (110) = 74° 6′, and *mm* (110) : (1$\bar{1}$0) = 73° 6′, are nearly equal to RR (100) : (010) = 74° 55′ of calcite; the acute negative bisectrix (with a very small axial angle) is nearly equally inclined to C (001), *m* (110), *m* (1$\bar{1}$0), so that under the microscope cleavage fragments of this mineral may easily be mistaken for calcite.

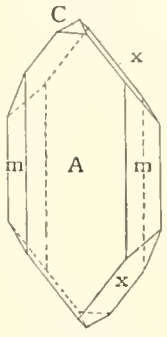

Fig. 555. — Barytocalcite, A {100}, *m* {110}, C {001}, *x* {121}.

The only substance which is dimorphous and belongs to both groups is $CaCO_3$; the hexagonal character of some $BaCO_3$, $SrCO_3$ and $PbCO_3$ is inferred from their presence in certain varieties of calcite; while an orthorhombic variety of $ZnCO_3$ is indicated by the presence of Zn in aragonite and cerussite.

Among the fibrous and massive carbonates of lime, fibrous varieties, and such as do not show well-defined cleavage, have generally been referred to aragonite.

THE BASIC CARBONATES

Chessylite.—Basic carbonate of copper; $2CuCO_3 . Cu(OH)_2$; CuO = 69·2. CO_2 = 25·6, H_2O = 5·2. Monoclinic.

$$a : b : c = 0{\cdot}850 : 1 : 1{\cdot}760. \quad \beta = 87° 36′.$$
$$m = \{110\}, \ C = \{001\}, \ k = \{111\}, \ l = \{013\}.$$
$$mm\ (110) : (1\bar{1}0) = 80° 41′, \ kk\ (111) : (\bar{1}11) = 73° 56′, \ Cm\ (001) : (110) = 88° 10′,$$
$$Ck\ (001) : (111) = 68° 12′, \ Cl\ (001) : (013) = 30° 24′.$$

Cleavage {011}, fair. Brittle. Fracture, conchoidal. H = 4; G = 3·8. Deep blue. Streak, smalt-blue. Lustre, vitreous. Translucent. Birefringence, positive; $\gamma - \alpha = 0{\cdot}2$. Axial plane perpendicular to (010). Acute bisectrix inclined at 15° to the normal of C and at 77° 24′ to the normal of A. 2E = 151°; $\rho > v$. Easily fusible (2). Soluble in hydrochloric acid.

With the above description compare crystals from **Chessy** (near Lyons, France).

Malachite.—Basic carbonate of copper; $CuCO_3 . Cu(OH)_2$; CuO = 71·9. CO_2 = 19·9, H_2O = 8·2. Monoclinic.

$$a : b : c = 0{\cdot}881 : 1 : 0{\cdot}401. \quad \beta = 61° 50′.$$
$$m = \{110\}, \ C = \{001\}, \ A = \{100\}.$$
$$AC\ (100) : (001) = 61° 50′, \ mm\ (110) : (1\bar{1}0) = 75° 40′.$$

Twinned on (100). Cleavage {010}, and {001}, perfect. Brittle. Fracture, uneven. H = $3\frac{1}{2}$; G = 4·0. Colour, emerald-green Streak, verdigris-green.

Lustre, sub-adamantine. Translucent; $\beta = 1{\cdot}88$. Birefringence, negative; $\gamma - \alpha = 0{\cdot}2$. Axial plane (010). Acute bisectrix inclined at 66° 30′ to the normal of A, and at 4° 40′ to the normal of C. $2E = 89°\ 18'$; $\rho < v$. Easily fusible (2). Soluble in hydrochloric acid.

With the above description compare crystals from **Rheinbreitbach** (near Coblenz).

Chessylite and **Malachite.**—The two basic carbonates of copper are striking minerals on account of their colour. Chessylite (*Germ.*

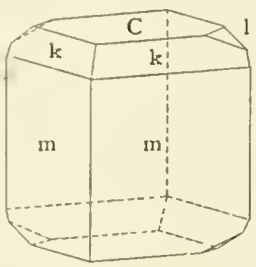

Fig. 556.—Chessylite, *m* {110}, C {001}, *k* {111}, *l* {013}.

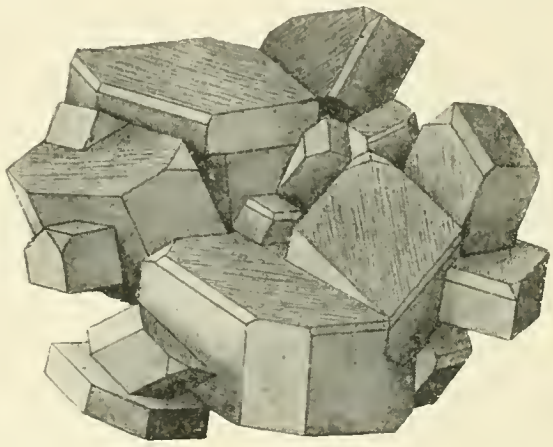

Fig. 557.—Chessylite from Chessy.

Kupferlasur, *Fr.* Azurite) derives two of its names from its remarkable blue colour; the English name is derived from the place Chessy, near Lyons, where the copper mines have yielded the most beautiful crystals known (Figs. 556 and 557); these are very perfect and have lustrous faces. The mineral is only transparent when very thin. The earthy varieties are of a lighter smalt-blue than the crystals.

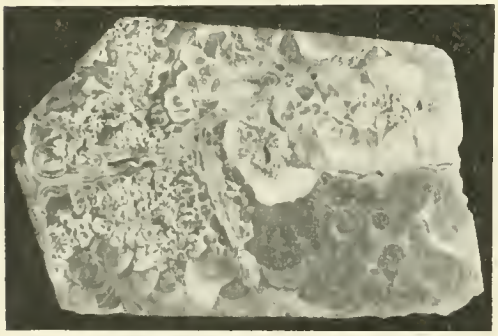

Fig. 558.—Malachite from the Urals.

Malachite (named from $\mu\alpha\lambda\acute{\alpha}\chi\eta$, the Greek for a mallow) is rarely crystallised, but is mostly found (*e.g.* at Nizhni Tagil and Gumeschev in the Urals) as compact or curvilaminar, nodular, mamillary and botryoidal masses. These sometimes have a fibrous structure. Fig. 558 is from a cut and polished specimen. Fibrous masses have a beautiful silky lustre. The best crystals are thin prisms found at Betzdorf in Westphalia and Dillenburg in Nassau; the former show the twinning very clearly.

Chessylite readily passes into malachite by loss of CO_2 and gain of water. Crystals from Chessy are sometimes transformed into malachite at one end, and the two minerals are almost invariably associated together. Malachite especially is a common decomposition product of

various copper ores, and the presence of copper minerals is generally indicated by blue and green decomposition products.

At Chessy, in addition to the crystals of Fig. 557, are found spherical concretions of chessylite, mostly about the size of a walnut, which consist of small crystals.

Near Clifton in Arizona stalactitic groups occur which consist of alternating concentric layers of malachite and chessylite.

Most of the malachite used for decorative purposes has been brought from the Urals, especially from the copper mines of Nizhni Tagil, where enormous quantities have been found. A mass in the School of Mines at St. Petersburg weighs 90 poods (= 3247 lbs.).

Note on the distinction between Calcite and Aragonite.

It has recently been shown that a simple and effective method of distinguishing between calcite and aragonite consists in boiling the powdered mineral with a dilute solution of cobalt nitrate; aragonite becomes lilac-red, whereas calcite becomes lavender-blue, or remains white or yellowish if traces of iron be present.

SECTION XV

SILICATES OF DIVALENT METALS

THE FERRO-MAGNESIAN SILICATES

THE OLIVINE GROUP

		a : *b* : *c*
Forsterite	Mg_2SiO_4	0·4648 : 1 : 0·5857
Olivine	$(Mg,Fe)_2SiO_4$	0·4657 : 1 : 0·5865
Fayalite	Fe_2SiO_4	0·4584 : 1 : 0·5793
Tephroite	Mn_2SiO_4	0·4600 : 1 : 0·5938

Olivine. — Silicate of magnesium and iron; $(Mg,Fe)_2SiO_4$; for Mg_2SiO_4 (forsterite), MgO = 57·1, SiO_2 = 42·9; for Fe_2SiO_4 (fayalite), FeO = 70·6, SiO_2 = 29·4; for $9Mg_2SiO_4.Fe_2SiO_4$ (chrysolite), MgO = 49·2, FeO = 9·8, SiO_2 = 41·0. Orthorhombic.

$$a : b : c = 0{\cdot}466 : 1 : 0{\cdot}586.$$

$$A = \{100\},\ B = \{010\},\ C = \{001\},\ m = \{110\},\ s = \{120\},\ d = \{101\},$$
$$e = \{111\},\ k = \{021\}.$$

$$mm\ (110) : (1\bar{1}0) = 49^\circ\ 57',\ Ad\ (100) : (101) = 38^\circ\ 27',\ de\ (101) : (111) = 20^\circ\ 2',$$
$$ss\ (120) : (1\bar{2}0) = 85^\circ\ 57'.$$

Twinned on (011). Cleavage {010}, {100}, imperfect. Brittle. Fracture, conchoidal. H = 7; G = 3·4. Yellowish-green. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1{\cdot}678$; $\gamma = 1{\cdot}697$. Birefringence, positive; $\gamma - \alpha = 0{\cdot}036$. Axial plane (001); acute bisectrix perpendicular to A (100). $2H = 106^\circ\ 20'$. Dispersion, slight; $\rho < r$. Infusible. Decomposed by hydrochloric acid.

With the above description compare crystals (chrysolite) from the **Red Sea** (?).

Forsterite occurs in colourless and yellow crystals, or in granular crystalline aggregates, with spinel in the volcanic ejections of Monte Somma (Mount Vesuvius).

Fayalite, or iron-olivine, is one of the commonest crystalline products of iron slags, in which it appears as tabular rhombs (combinations of B, *k*, and *m*), black and opaque, but possessing a typical vitreous lustre. It is also found in small crystals in the rhyolite of the Yellowstone National Park (Wyoming), and in nodules in the granite of the Mourne Mountains in Ireland. The name fayalite was originally given

to a substance from Fayal Island in the Azores, which may, however, be only an iron slag originally brought to that coast as ship's ballast.

Tephroite is found as a gray cleavable mineral, together with zincite, willemite, and franklinite at Franklin (New Jersey), and with rhodonite and other manganiferous minerals at Pajsberg in Sweden. It was named from its colour (τεφρός = ash-coloured).

Numerous mixtures of these compounds with each other, and with the analogous calcium compound, which is not found as a distinct mineral, constitute the remainder of the olivine group. Among these the best defined is **monticellite**, $MgCaSiO_4$, a very rare mineral found in yellowish crystals at Mount Vesuvius, which may be a double salt, since the analysis corresponds to one molecule of forsterite united with one of Ca_2SiO_4.

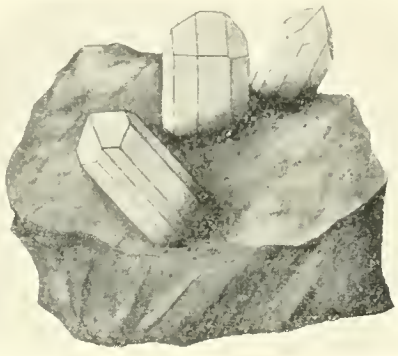

Fig. 559.—Olivine (serpentinised) from Snarum (Norway).

Olivine is generally made to include the mixtures having the constitution $n Mg_2SiO_4 + Fe_2SiO_4$ where n varies from 12 to 3.

In all these minerals the axial plane is (001) and the optic axes emerge nearly normal to the faces s, the true angle 2V being 87° 46′ (Na-light) for olivine.

Green crystals with a yellow metallic surface, due to alteration, found in the limburgite of the Kaiserstuhl near Freiburg in Baden, are distinguished by the name "hyalosiderite"; in these $n = 2$ and the crystalline form is slightly different: mm (110) : (1$\bar{1}$0) = 50° 10′, instead of 49° 57′; this may be another double salt.

Some olivine is titaniferous, owing probably to intermixture with an isomorphous titanate.

Olivine is but rarely found crystallised on a large scale, but in some of the more basic eruptive rocks (basalts, etc.) well-defined small crystals are very common, and may be recognised by their typical form in microscopic sections; this, with the high refractive index, strong double refraction, large axial angle, and very imperfect cleavage, serves to identify the mineral, and distinguish it from augite. In consequence of these characters, sections of olivine present a high relief, like garnet and sphene, and polarise in bright colours of the second order.

In rock-specimens it is generally discernible by the eye as greenish to reddish glassy blebs and grains.

Olivine is an essential constituent of very many of the basic and ultrabasic rocks, and is, in fact, one of their most characteristic minerals.

In the rocks of granitic texture (olivine-gabbros, olivine-norites, peridotites, etc.) it usually occurs in crystalline grains; in those of trachytic texture (dolerites, basalts, etc.) it usually presents very symmetrical crystals of elongated hexagonal section. In these rocks it has always been one of the earliest minerals to crystallise. Large greenish

patches of olivine are conspicuous in many basalts, *e.g.* that of Unkel in Rhenish Prussia, and in some of the Vesuvian lava.

Among the ultra-basic rocks it is sometimes the predominant mineral, and associated with diallage or bronzite may constitute an "olivine-rock"; at Dun Mountain (New Zealand), it occurs in such quantity, associated with chromite alone, that it constitutes a rock mass, which is known by the name of "dunite." In the basic rocks it is usually associated with other ferro-magnesian minerals. Olivine is also found in certain talc-schists and in the granular limestones associated with the crystalline schists; it is also one of the important constituents of meteorites.

Twinning (on 011 or 012) is very rare, and is almost confined to the microscopic crystals found in rock sections.

Olivine gelatinises with acids, the most ferriferous varieties yielding most easily; these are also the most fusible.

Olivine is particularly liable to suffer alteration into serpentine, a massive magnesian silicate (p. 438), $H_4Mg_3Si_2O_9$, and most serpentine has been derived from the decomposition of olivine rocks.

At Snarum in Norway, in the serpentine, have been found the large greenish crystals represented in Fig. 559. These consist almost entirely of pure serpentine, and when first discovered were supposed to be crystals of that mineral. But they have the form of the olivine from Vesuvius, though on a larger scale, and sometimes contain a kernel of unaltered olivine, so that their derivation from that mineral is placed beyond doubt. Olivine can usually be recognised in rock sections by its partial decomposition into serpentine; owing to the absence of well-defined cleavage it is usually traversed by irregular cracks, and the incipient decomposition proceeds along these cracks and fills them with green serpentine or brown ferric hydrates.

Chrysolite, an old classical name, which in Pliny refers probably to topaz, is now usually restricted to the clear yellow or green crystals of olivine brought from the East for use in jewellery. The locality of these is unknown, but they are said to come from the Red Sea. They are tabular crystals, owing to the predominance of A {100}, which is vertically striated; the so-called chrysolite from Brazil and Ceylon is mostly chrysoberyl.

Olive-green and bottle-green crystals of olivine are also used in jewellery, and are generally known as "peridote," an old name for the mineral.

SECTION XVI

SILICATES OF DIVALENT METALS

THE FERRO-MAGNESIAN SILICATES (*Continued*)

THE PYROXENE GROUP

The name pyroxene was originally given by Haüy to certain greenish crystals found in the lavas of Vesuvius, Etna, and Auvergne, and also at Arendal in Norway. He mentioned as their essential feature a cleavage of about 88°, and gave the name, "stranger to fire" (from πῦρ and ξένος) as an indication of his opinion that they were only accidentally caught up in the lavas which contain them. The name is a misnomer, for pyroxene is one of the most characteristic minerals of a large group of basic igneous rocks. Many minerals which have been described under different names and as of very different composition have been referred to pyroxene, and the name is now conveniently used for a whole group. The old names are still used to distinguish the various members of this important group, now that they are classified according to their chemical composition.

The pyroxene group includes minerals which, except when they contain alumina, can be referred to the type $R''SiO_3$, and possess a ready cleavage of about $87\frac{1}{2}°$; they form a well-defined group of minerals passing into each other by a series of intermediate isomorphous mixtures; they include minerals belonging to no less than three different systems.

MONOCLINIC PYROXENES

Diopside.—$CaMg(SiO_3)_2$; CaO = 25·9, MgO = 18·5, SiO_2 = 55·6. Monoclinic; symmetry, equatorial (?).

$$a : b : c = 1·0921 : 1 : 0·5893. \quad \beta = 74° 10'.$$

$$m = \{110\}, \ A = \{100\}, \ B = \{010\}, \ C = \{001\}, \ u = \{111\}, \ p = \{10\bar{1}\},$$
$$s = \{\bar{1}11\}, \ o = \{\bar{2}21\}.$$

mm $(110) : (\bar{1}10) = 87° 12'$, AC $(100) : (001) = 74° 10'$, uu $(111) : (1\bar{1}1) = 48° 29'$, ss $(\bar{1}11) : (111) = 59° 11'$, C$p$ $(00\bar{1}) : (10\bar{1}) = 31° 20'$, C$u$ $(001) : (111) = 33° 49'$, Cm $(001) : (110) = 79° 9'$, mo $(110) : (\bar{2}21) = 35° 30'$, so $(\bar{1}11) : (221) = 58° 49'$.

Twinned on (100). Cleavage $\{110\}$, perfect; (100), (010), imperfect. Brittle. Fracture, conchoidal. H = $5\frac{1}{2}$; G = 3·3. Light green. Streak, white. Lustre, vitreous. Transparent. $\beta = 1·681$, $\gamma = 1·703$. Birefringence, positive, strong; $\gamma - \alpha = 0·030$. Axial plane (010); acute bisectrix inclined at 21° 45′ to the

normal of C and 52° 25′ to the normal of A. $2E = 112°$; $\rho > v$. Fusible. Insoluble in acids.

With the above description compare crystals from **Ala** (Piedmont) (Fig. 561).

Augite contains Al_2O_3 and Fe_2O_3 in addition to the constituents of diopside. Colour, black. Characters nearly the same as those of diopside.

With this description compare crystals from **Schima** in Bohemia (Fig. 560).

Diopside. — The character of a typical pyroxene may best be studied in the clear green crystals of diopside which are found, with crystallised garnet, in a mass of garnet rock in the Ala valley in

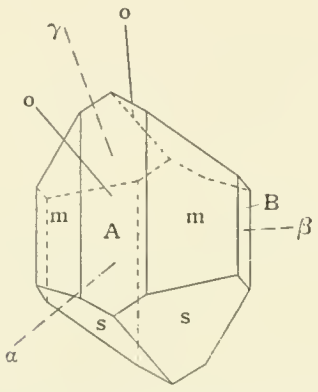

Fig. 560.—Augite, A {100}, *m* {110}, B {010}, *s* {111}.

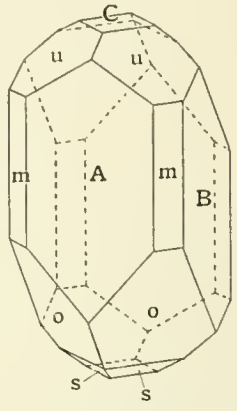

Fig. 561.—Diopside, A {100}, *m* {110}, B {010}, C {001}, *u* {111}, *o* {22$\bar{1}$}, *s* {111}.

Piedmont (Fig. 566). They are generally a combination of B {010}, A {100}, *m* {110}, *u* {111}, *o* {22$\bar{1}$}, C {001}, of the habit shown in Fig. 561. The face C is quite dull. The pale green crystals are often of a darker green at one end, and this seems to be accompanied by the development of certain faces at that end, as though the crystals might

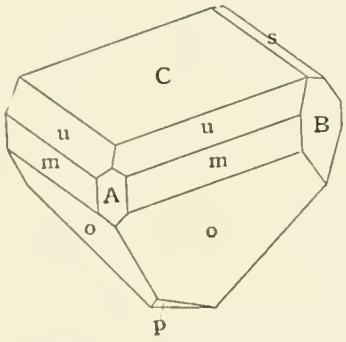

Fig. 562.—Diopside, A {100}, *m* {110}, B {010}, C {001}, *u* {111}, *s* {111}, *o* {22$\bar{1}$}, *p* {10$\bar{1}$}.

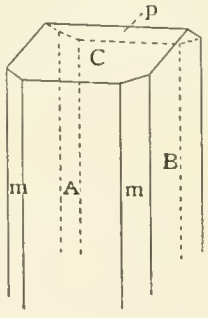

Fig. 563.—Augite, A {100}, *m* {110}, B {010}, C {001}, *p* {10$\bar{1}$}, from Nordmarken.

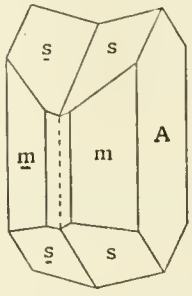

Fig. 564.—Augite twinned on (100).

be differently terminated at the two ends (Class III. p. 280). Crystals possessing only a plane and not an axis of symmetry have, in fact, been found in Orange Co. (New York), terminated at one end by {001}, {111}, and at the other by {221}, {101} (Fig. 562).

Twinning on A is common; either two individuals are united by this face (Fig. 564), or a crystal is traversed by twin lamellæ parallel to it. There are sometimes also twin lamellæ parallel to C {001}.

The following is an analysis of a colourless crystal from Ala:—

SiO_2.	CaO.	MgO.	FeO.
54·74	26·03	17·02	2·91

indicating a nearly pure silicate of lime and magnesia, with only a slight replacement of the latter constituent by ferrous oxide.

The extinction on *B* is 36° 5′ (= $c\gamma$).

A colourless diopside from Nordmarken in Sweden, which is nearly identical with the Ala mineral in composition, gave an extinction of 38° 3′. It is not certain what would be the exact extinction angle of a pure diopside containing no iron.

Other minerals which, as being mainly lime-magnesia silicates, may be termed diopside, contain a much larger proportion of iron, and sometimes also manganese, and the change in composition is accompanied by a change of physical characters.

The following observations were made by Doelter on (A) a dark green pyroxene from Nordmarken, and (B) on a dark-coloured massive pyroxene from Tunaberg in Sweden, to which the name hedenbergite (after the Swedish chemist Hedenberg) was given by Berzelius before the mineral was known to belong to the pyroxene family.

	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	CaO.	MgO.	Extinction $c\gamma$.
(A)	50·91	0·17	0·76	17·34	22·93	7·21	+ 46° 45′
(B)	47·62	1·88	0·10	26·29	21·53	2·76	+ 47° 50′

Here an increase in the percentage of iron seems to involve an increase in the extinction angle; other observations have supported this conclusion.

In the above two analyses a new feature is introduced, for small percentages of the sesquioxides begin to make their appearance; it is, in fact, found that very many pyroxenes contain varying proportions of alumina and ferric oxide, which may even rise to as much as 20 per cent. Rammelsberg, in 1858, urged the necessity of distinguishing between the ferrous and ferric oxide in the analysis of pyroxenes, and the analyses subsequent to that date enable us now to divide the monoclinic pyroxenes into two classes: (1) diopsides, or pyroxenes containing no sesquioxides, and (2) augites, or pyroxenes in which sesquioxides are present.

Many diopsides can be represented as a combination of one molecule $CaSiO_3$ with one molecule $MgSiO_3$; but a consideration of the ferriferous diopsides led Wülfing to the conclusion that the members of this series are to be regarded as isomorphous mixtures, in varying proportions, of the silicates $CaMgSi_2O_6$, $CaFeSi_2O_6$, and $MgFeSi_2O_6$. The first of these is the diopside proper from Ala; the second is the mineral referred to above as hedenbergite; the third is not known among the

monoclinic pyroxenes as a distinct mineral, neither are the corresponding manganese compounds.

In the manganiferous diopsides (sometimes distinguished by the name schefferite) an increase of manganese acts like the increase of iron and makes the extinction angle larger. Flink found this angle to be as much as 69° for a ferriferous schefferite from Pajsberg in Sweden.

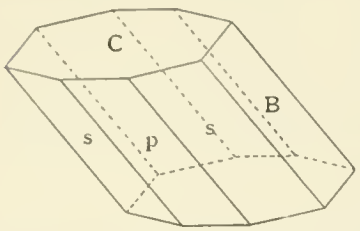

Fig. 565.—Schefferite, B {010}, C {001}, *p* {101}, *s* {111}.

Augite, a word borrowed from Pliny, was a name used before pyroxene and applied to the dark opaque crystals found in many basaltic lavas; these were distinguished from tourmaline and hornblende and recognised as a separate species by Werner about 1792.

Typical augite occurs as black porphyritic crystals in basalt and basaltic rocks in many parts of the world; the habit is usually that of Fig. 560, and the crystals are often twinned on A {100}, as in Fig. 564. When the basalt decomposes into a clayey material the augite is left as separate crystals, and such specimens are to be found in all mineral collections; such are the crystals from Bilin and other Bohemian localities, and those from Mount Bufaure in the Fassathal (Tyrol). The latter, which are found as porphyritic constituents of an altered melaphyre, have curved faces of *n* {102}, which in the twinned crystals form a rounded termination to one end of the twin.

These black basaltic augites exactly resemble the basaltic hornblendes in colour and appearance, but may be distinguished from them by the nearly rectangular cleavage. In thin fragments or sections they are brown and transparent, and the mineral is easily recognised in microscopic sections by its high relief, brown colour, and the cleavage cracks. It will be seen from Fig. 560 and from the description on p. 164 that one optic axis emerges nearly normal through the basal plane C, and the other obliquely through the ortho-pinakoid A. Hence sections perpendicular to the prism *m* will exhibit a series of nearly rectangular cleavage cracks (Fig. 566), whose angles are bisected by the extinction directions, and viewed in convergent light they show an optic axis nearly central; sections parallel to A give parallel cleavage cracks, straight extinction, and an optic axis near the edge of the field of view. If the latter sections are from a twin crystal and so consist of two overlapping plates, then in the extinction position each plate will contribute an optic axis, and the interference figure may be mistaken for that of a biaxial crystal cut perpendicular to the acute bisectrix; if it be viewed by monochromatic light, the form of the rings in the diagonal position will at once show it to be a composite figure.

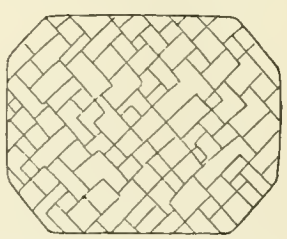
Fig. 566.—Augite, section perpendicular to the prism zone.

As in the diopsides, so also in the augite series, the optical characters change with the composition; the extinction angle on the clino-pinakoid

B varies from about 37° to 50°; generally speaking, it seems to increase with the percentage of iron.

It has long been a matter of doubt what is the alumo-silicate isomorphous with diopside which enters into the composition of the augite group; the analyses are now generally explained (following the suggestion of Tschermak) as isomorphous mixtures of the diopside molecule $CaMgSi_2O_6$ with the alumo-silicate $R''Al_2SiO_6$ (or $R''Fe_2SiO_6$).

The observations of Doelter show that if a curve be constructed with the extinction angles for abscissæ and the percentages of ferrous oxide for ordinates, it is not a continuous curve; his analyses can, however, be expressed as mixtures in varying proportions of the diopside molecule with the silicates $CaFeSi_2O_6$, $MgFe_2SiO_6$, $MgAl_2SiO_6$, and $Na_2Al_2SiO_6$, and if the sum of the four last be taken for ordinate a continuous curve is obtained. It appears, therefore, that in the augite series the extinction angle on B increases as the proportion of the silicate $CaMgSi_2O_6$ diminishes, and this was shown above to be also true of the diopside series.

The extinction angle is a character easily measured, and useful for the purpose of distinguishing the mineral in cleavage fragments or sections; the variation of the other optical characters and of the specific gravity in the pyroxene group is illustrated in the following table by the minerals which have already been mentioned above.

The extinction angle on cleavage flakes *m* will, in accordance with the diagram on p. 144, depend upon the optic axial angle 2V and the angle $c\gamma$. The latter may vary from about 36° to 54°.

	β.	$\gamma - \alpha$.	$2E_{Na}$.	Extinction on *m*.	Spec. Grav.
Diopside, Ala . .	1·680	0·029	112°	34°	3·30
Hedenbergite, Tunaberg	1·737	0·019	120°	42°	3·492
Augite, Nordmarken .	1·690	0·030	120°	34°	3·311

The pleochroism of the pyroxenes is extremely slight, and until recently the usual character employed in distinguishing a pyroxene from an amphibole in rock sections was the pleochroism of the latter; but, in reality, coloured diopsides and augites generally show distinct change of colour when rotated on the microscope stage above the polariser.

In addition to the diopside of Ala and of New York, other specimens of monoclinic pyroxene occasionally show a difference of termination at the two ends of the prism, indicating that the mineral probably possesses only a plane of symmetry and not a digonal axis perpendicular to it; and therefore belongs to Class III. of pp. 280-81. This has been confirmed by the etching figures produced on the prism faces by hydrofluoric acid; the mineral is, however, generally holosymmetric in appearance. The monoclinic pyroxenes frequently possess a lamellar structure parallel

to C (001), due to twinning on that face; the varieties from Sala in Sweden, and from Mussa-Alp in the Ala valley, possess a sort of cleavage parallel to A (100) and C (001); this is found to be in reality not a true cleavage, but a "parting" due to the fact that these faces are glide planes and planes of secondary twinning; the parting only takes place at intervals and not uniformly through the whole mass of the crystal, as would be the case with a true cleavage. These parting faces have been the subject of much study, and are now supposed to be due to pressure. Massive specimens often exhibit this lamellar structure.

Some Noteworthy Localities:

Ala (Piedmont).—Clear green diopside of the habit of Fig. 567 (sometimes also resembling Fig. 563) occurs with crystallised red garnet and scaly chlorite, lining cavities in a mass of garnet rock which contains grains of diopside and chlorite, and traverses the serpentine. The contrast between the pale green diopside, the rich red garnet and dark green chlorite, makes this one of the most beautiful mineral associations to be found in collections. Fig. 567 is from a specimen in the British Museum.

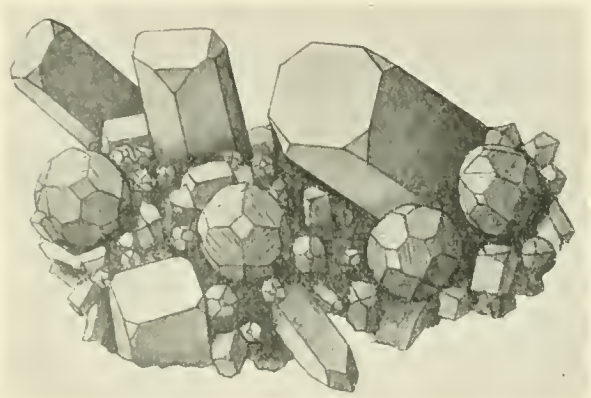

Fig. 567.—Diopside with Garnet, from Ala.

Mount Vesuvius.—Some of the Vesuvian lavas contain porphyritic black crystals like Fig. 560. In the ejected blocks of **Monte Somma**, beautiful crystals, colourless, yellow, brown or black, are found lining druses with sanidine, anorthite, leucite, nepheline, etc. Some of these are very rich in faces, and the habit may be that of Fig. 561 or Fig. 563.

Nordmarken (Sweden).—Dark green or black crystals of considerable size, resembling Fig. 563, line cavities in the massive green granular pyroxene of the magnetite iron mines. With them are associated magnetite, chlorite, and sometimes blende.

Acmite, or ægirite, is a remarkable monoclinic member of the pyroxene group which may be described as an alkali diopside. This mineral has the composition $NaFeSi_2O_6$, corresponding to

Na_2O.	Fe_2O_3.	SiO_2.
13·4	34·6	52·0

The axial angle β is 73° 11′, instead of 74° 10′, as in diopside. It differs also in its optical characters from diopside and augite. The birefringence is negative; $\beta = 1{\cdot}780$; $2E = 134\frac{1}{2}°$. The extinction angle

on B ($c:a$) is about 5°. Pleochroism, α deep green, β pale green, γ yellow. Readily fusible.

The original acmite occurs in dark brown or green prisms, often bent and broken, in quartz, in pegmatitic veins of the granite of Eker in Norway; the form is shown in Fig. 568. It is characterised by steep pyramids, whence its name, from *ἀκμή*, a point; o is $\{\bar{6}61\}$. This figure is reversed in order to show the forms more clearly. The name ægirite is given to the variety which occurs as a constituent of the augite syenites and elæolite syenites of Norway; some of the rocks in the Christiania district consist mainly of ægirite and felspar, often with quartz and nepheline; and similar rocks are found in Abyssinia and Madagascar. The pleochroism of ægirite is, α grass green, β pale green, γ brown, and is very characteristic of the mineral.

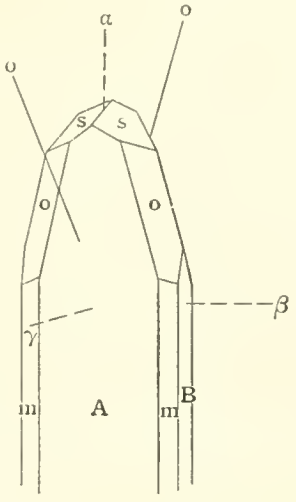

Fig. 568.—Acmite, A $\{100\}$, m $\{\bar{1}10\}$, B $\{0\bar{1}0\}$, s $\{\bar{1}11\}$, o $\{661\}$.

ORTHORHOMBIC PYROXENES

Enstatite.—Silicate of magnesium; $MgSiO_3$; $MgO = 40{\cdot}0$, $SiO_2 = 60{\cdot}0$, also contains FeO. Orthorhombic.

$$a:b:c = 0{\cdot}970 : 1 : 0{\cdot}570.$$

$$mm\ (110) : (1\bar{1}0) = 88°\ 20'.$$

Cleavage $\{110\}$, $\{010\}$. Brittle. Fracture, uneven. H $= 5\frac{1}{2}$; G $= 3{\cdot}2$. White. Streak, white. Lustre, vitreous. Translucent; $\beta = 1{\cdot}659$. Birefringence, weak, positive; $\gamma - \alpha = 0{\cdot}009$. Axial plane (010); acute bisectrix normal to (001). $2H = 79°$; $\rho < r$. Infusible. Insoluble in acids.

With the above description compare imperfect prisms from **Mount Zdjar** in Moravia.

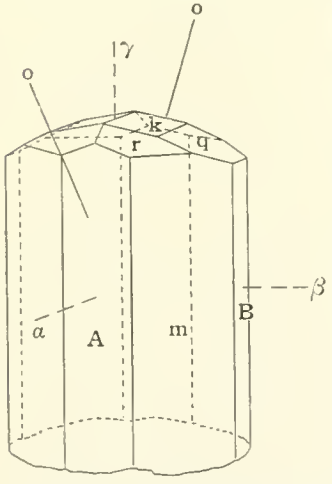

Fig. 569.—Enstatite, A $\{100\}$, m $\{110\}$, B $\{010\}$, k $\{012\}$, q $\{023\}$, r $\{223\}$.

The mineral from Mount Zdjar in Moravia was described by Kenngott under the name **enstatite** in 1855; it had previously been regarded as a scapolite; and he pointed out the close chemical relationship between this mineral, the augites, and two other substances which had been known since the time of Haüy as hypersthene and bronzite; the latter were lamellar and fibrous minerals without definite crystalline form, and therefore difficult to place in the system. Hypersthene and bronzite only differ chemically from enstatite in containing Fe replacing Mg. Des Cloizeaux showed from the optical characters that these three minerals are orthorhombic, and the timely discovery by

von Lang (1871) of measurable crystals in a meteorite which fell at Breitenbach in Bohemia completed the determination of the species. In the same year small tabular crystals found in a volcanic ejected block at Laach in Rhenish Prussia were described by vom Rath under the name amblystegite, on account of their flat dome terminations, and these were soon found to be identical with the enstatite of the meteorite.

Subsequently (1874) enormous crystals (Fig. 569), found in the apatite-bearing schists of Bamle in Norway, were identified by Brögger and vom Rath as also enstatite. These observations established the existence of a group of rhombic pyroxenes.

They differ from the monoclinic pyroxenes in having straight extinction through both prism and {010}, whereas an augite has an extinction of 40° 50′ through (010) and of about 35° through (110); they exhibit a well-marked cleavage or parting parallel to {010}; they are much more pleochroic than augite, α reddish-brown, β yellowish-brown, γ green. These characters serve to identify enstatite in sections of certain trachytes, andesites, etc., in which it occurs as an essential constituent of the rock.

ANORTHIC PYROXENE

Rhodonite.—Silicate of manganese; $MnSiO_3$; $MnO = 54{\cdot}1$, $SiO_2 = 45{\cdot}9$. Anorthic.

$$a : b : c = 1{\cdot}073 : 1 : 0{\cdot}621.$$

$$\alpha = 103° 18', \beta = 108° 44', \gamma = 81° 39'.$$

$m = \{110\}$, $M = \{1\bar{1}0\}$, $C = \{001\}$, $B = \{010\}$, $n = \{22\bar{1}\}$, $k = \{2\bar{2}\bar{1}\}$.

$mM\,(110) : (110) = 87° 32'$, $Cm\,(001) : (110) = 68° 45'$, $CM\,(001) : (1\bar{1}0) = 86° 24'$.

Cleavage $\{1\bar{1}0\}$, $\{110\}$, perfect; $\{001\}$, fair. Brittle. Fracture, uneven. $H = 6$; $G = 3{\cdot}6$. Flesh-red. Streak, white. Lustre, vitreous. Translucent; $\beta = 1{\cdot}73$. Birefringence, negative, weak; $\gamma - \alpha = 0{\cdot}010$. Axial plane inclined at 63° to M and 38° to C; acute bisectrix inclined at 51° 47′ to the normal of M and 51° 40′ to the normal of C. $2H = 79°$; $\rho < v$. Fusible ($2\frac{1}{2}$). Partly soluble in hydrochloric acid.

With the above description compare crystals from **Långban** in Sweden.

This mineral receives its name from the beautiful red colour, and is used for an ornamental stone, especially in Russia, where it is quarried in large quantities in the Ural Mountains. It generally contains a considerable proportion of calcium and iron; the former is sometimes due to intermixed calcite, which may be detected by effervescence with acids; the iron may be due to an intermixture of the isomorphous ferrous silicate $FeSiO_3$, **babingtonite**, which is found as small black crystals in Norway and at the Haytor Iron Mines in Devonshire, where it was formerly worked as an iron ore.

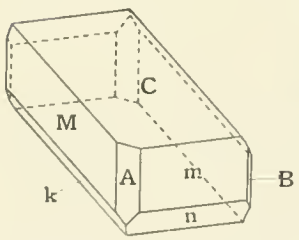

Fig. 570.—Rhodonite, A {100}, C {001}, m {110}, M {110}, B {010}, n {22$\bar{1}$}, k {2$\bar{2}$1}.

The rhodonite from the zinc mines of Sterling Hill (New Jersey),

contains about 6 per cent of ZnO, and is known as fowlerite; it occurs (sometimes in large crystals) with franklinite in limestone.

THE AMPHIBOLE GROUP

The minerals referred to this group are very similar in composition to the pyroxenes; some of the Fe, Mg compounds have indeed the same composition $(Fe,Mg)SiO_3$. But they differ from the pyroxenes in possessing a cleavage of about 56° instead of 87°. The name amphibole was introduced by Haüy (*ἀμφίβολος* = doubtful) to replace schorl, a mining term which was applied both to the black tourmaline and to hornblende; these two minerals resemble each other closely in form. Hornblende is also an old mining name. Haüy's name, amphibole, like pyroxene, may be conveniently retained for the whole group.

Since the cleavage angle of common hornblende is 55° 49′, and the angle of the prism {210} in augite is 55° 26′, it has often been supposed that the two are really the same mineral, and merely differ in their forms and in their cleavage. Rose showed that when hornblende is fused, it re-crystallises as augite.

That the two are, however, to be regarded as different minerals was settled by a study of uralite, a mineral having the faces of augite and the cleavage of hornblende; this is clearly an alteration product—a pseudomorph of hornblende after augite. Further, the lime-magnesia silicate, tremolite, in the amphibole group, while conforming to the formula $R''SiO_3$, like the corresponding compound, diopside, in the pyroxene group, really has a different composition, for whereas diopside is $CaMg(SiO_3)_2$, tremolite is $CaMg_3(SiO_3)_4$.

The amphibole group, then, contains minerals which possess a ready cleavage of about 56°, and, except when they contain alumina, can be referred to the type $R''SiO_3$; like the pyroxenes, they form many isomorphous mixtures, and belong to the same three systems.

MONOCLINIC AMPHIBOLES

Tremolite. — $CaMg_3(SiO_3)_4$; $CaO = 13{\cdot}45$, $MgO = 28{\cdot}83$, $SiO_2 = 57{\cdot}72$. Actinolite contains also FeO. System, monoclinic.

$$a : b : c = 0{\cdot}551 : 1 : 0{\cdot}294. \quad \beta = 73° 58'.$$

$m = \{110\}$, $A = \{100\}$, $B = \{010\}$, $r = \{011\}$, $p = \{101\}$, $e = \{130\}$, $t = \{101\}$.

mm $(110) : (1\bar{1}0) = 55° 49'$, rr $(011) : (0\bar{1}1) = 31° 32'$, pr $(101) : (0\bar{1}1) = 34° 25'$.

Twinned on A (100). Cleavage {110}, perfect; {100}, {010}, imperfect. Brittle. Fracture, uneven. $H = 5\frac{1}{2}$; $G = 3{\cdot}1$. Pale green. Streak, gray. Lustre, vitreous. Translucent; $\beta = 1{\cdot}62$, $\gamma = 1{\cdot}63$. Birefringence, negative, strong; $\gamma - \alpha = 0{\cdot}028$. Axial plane (010); acute bisectrix inclined at 15° to normal of A (100), and almost parallel to (001), or the edge rr. $2V = 85°$, $\rho < v$. Fusible. Insoluble in acids.

With the above description compare crystals from **Russell** (New York). Fig. 572 (*cf.* Fig. 571).

Hornblende contains Al_2O_3 and Fe_2O_3 in addition to the constituents of tremolite. Colour, black. Characters nearly the same as those of tremolite.

With the above description compare crystals from **Schima** (Bohemia).

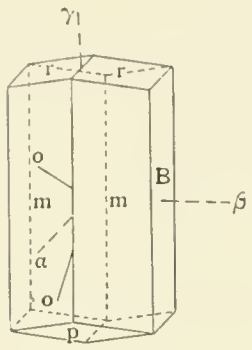

Fig. 571.—Hornblende, m {110}, B {010}, r {011}, p {101}.

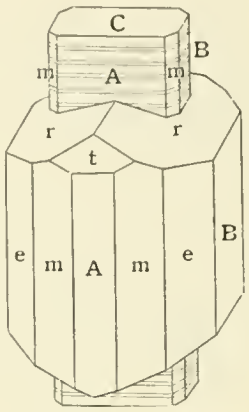

Fig. 572.—Amphibole enclosing parallel Pyroxene, A {100}, B{010} m {110}, e {130}, t {101}, r {011}, C {001}, from New York.

Tremolite and the other non-aluminous amphiboles corresponding to diopside are mostly columnar and fibrous crystals without definite terminations. The name tremolite was given in allusion to the Val Tremola (St. Gothard); the true tremolite, however, corresponding to the composition $CaMg_3(SiO_3)_4$, occurs not here but in the granular white dolomite of Campolongo (Tessin), where it is found as white or greenish translucent crystals, a combination of m B, in long blade-like prisms with vertical striations.

Green crystals found in limestone at Russell in New York are well terminated and have the forms shown in Fig. 572 ($e = \{130\}$, $t = \{101\}$). These, as well as green crystals from Gouverneur and brown crystals from Pierrepont, have nearly the composition given above for tremolite.

Fig. 572 also shows how the Russell crystals are intergrown in parallel position with pyroxene, the faces A and B being parallel in each. The basal plane C of the pyroxene is nearly parallel to the edge rr ($= 011 : 011$) of the tremolite. For this reason r is taken as $\{011\}$; it has formerly been the custom to place the amphiboles in the reverse position, and to make r $\{111\}$.

True tremolite is quite pale in colour; as the proportion of iron increases, the colour becomes a darker green; the name actinolite (*Germ.* Strahlstein) is given to the varieties which contain a considerable proportion of FeO, up to about 25 per cent. Actinolite is also markedly pleochroic, γ = green, β = yellowish-green, α = greenish-yellow; the optical orientation and the refractive indices are practically the same as for tremolite. Actinolite is a very common mineral in the crystalline schists; it is usually found in columnar or fibrous aggregates.

Hornblende, the common black mineral corresponding to augite in the pyroxene group, contains alumina and generally ferric iron. It is

a constituent of syenites and diorites, and of many crystalline schists. Amphibolite and hornblende-schist consist entirely of this mineral.

The properties of the mineral are best studied in the variety known as basaltic hornblende, which occurs in porphyritic crystals in some andesites, trachytes, and basalts; it is these crystals, of the habit shown in Fig. 571, which were formerly confused with tourmaline, and known as schorl.

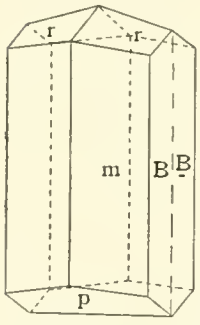

Fig. 573.—Hornblende twinned on (100).

Excellent crystals are found weathered out of the altered basalts of Bilin and Schima in Bohemia, very similar in appearance to the augites from the same locality mentioned on p. 420. They are often twinned on (100), as in Fig. 573. The twin crystals may be easily recognised as terminated at one end by two faces (*p*), at the other by four faces (*r*), instead of by three, as in Fig. 571. Lamellar twinning parallel to (001), like that of pyroxene, is very rare in amphibole.

These basaltic hornblendes are characterised by a very low extinction angle on B (angle between a and normal to (100), or between γ and the edge B*m*), which sinks to a few degrees as compared with the usual angle, 15°, for amphibole, and also by a very strong pleochroism, γ = dark brown, a = yellow; but since these properties are acquired by ordinary hornblendes on heating, and in all the basaltic hornblendes the extinction angle may be reduced to zero by heating in super-heated steam, it is possible that they are only due to alteration, and are acquired characters.

Under the microscope, cross sections of amphibole in rocks are easily recognised by the characteristic cleavage cracks of Fig. 574; if the section is at right angles to the prism zone, their angle is about 56°, and is bisected by the extinction directions; viewed in convergent light they give a positive obtuse bisectrix inclined at about 15° to the normal.

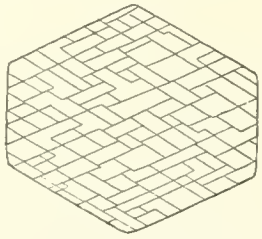
Fig. 574.—Hornblende, section perpendicular to the prism zone.

The composition of the aluminous amphiboles has not yet been so satisfactorily made out as that of the aluminous pyroxenes. They cannot all be explained by importing the molecule $R''Al_2SiO_6$ which sufficed for the pyroxenes. Tschermak introduces, in addition to the tremolite molecule $CaMg_3(SiO_3)_4$, the molecules $CaMgAl_4(SiO_6)_2$ and $CaMg_2Al_2(SiO_4)_3$. Groth makes hornblende a mixture of $(SiO_3)_2Mg_3Ca(SiO_3)_2$ and $(SiO_3)_2Mg_2Al_2(AlO)_2$. Scharizer found a variety from Jan Mayen Island, with an extraordinarily high percentage of sesquioxides, to have the composition $R''_3Al_2Si_3O_{12}$; to this he gave the name "syntagmatite," previously used for the Vesuvian hornblende, which has a somewhat similar composition, and suggested that all the amphiboles may be regarded as isomorphous mixtures of the tremolite and syntagmatite molecules.

This amphibole, like many others, contains a certain percentage of alkalis, of which two atoms are generally supposed to replace one atom of calcium of the non-alkaline varieties.

There are several rare alkali hornblendes comparable with acmite. **Arfvedsonite** is a soda-amphibole found in large black crystals in the nepheline syenite of Kangerdluarsuk (Greenland), and in similar rocks elsewhere. It is strongly pleochroic. **Glaucophane** is a blue pleochroic mineral found in grains in certain mica-schists, gneisses, and phyllites; it has the composition $NaAlSi_2O_6 . RSiO_3$ where R = Fe, Mg, Ca, corresponding to the union of a molecule of the acmite type with one of the enstatite type. **Riebeckite**, $2NaFeSi_2O_6 . FeSiO_3$, is another blue pleochroic amphibole of similar constitution found under much the same conditions as ægirite.

Some Noteworthy Localities:

The characteristic occurrences of **New York**, **Campolongo**, and **Bilin** have been mentioned above.

Vesuvius.—The sharp, brilliant, black crystals, called syntagmatite, occur with augite and mica, sometimes also idocrase and garnet, in cavities of the sanidine blocks of **Monte Somma.** They are rather flat prisms owing to the predominance of the *m* faces, and the absence of B, and are usually terminated like Fig. 571.

ORTHORHOMBIC AMPHIBOLE

A mineral known as **anthophyllite** corresponds to enstatite and has the composition $(Mg,Fe)SiO_3$; the best specimens are found as brownish, fibrous, and flaky masses with hornblende, tremolite, and biotite, in a mica schist at Kongsberg in Norway. The pinakoidal cleavage {010} is less conspicuous in anthophyllite than in enstatite; the pleochroism is also less marked; the birefringence is greater, $\gamma - \alpha = 0{\cdot}024$.

ANORTHIC AMPHIBOLE

The only anorthic amphibole corresponding to rhodonite and babingtonite is a very rare mineral, known as **ænigmatite**, found in large black crystals in the elæolite syenite of Julianehaab in Greenland. It possesses a cleavage of 65° 55′, and is a titano-silicate of sodium, iron, and aluminium.

GENERAL SURVEY OF THE PYROXENE AND AMPHIBOLE GROUPS

PYROXENE GROUP		AMPHIBOLE GROUP	
Orthorhombic		*Orthorhombic*	
Enstatite	$MgSiO_3$	**Anthophyllite**	$(Mg,Fe)SiO_3$
Hypersthene	$(Mg,Fe)SiO_3$		
Monoclinic		*Monoclinic*	
Diopside	$MgCa(SiO_3)_2$	**Tremolite**	$CaMg_3(SiO_3)_4$
Augite	$CaMg(SiO_3)_2$, $MgAl_2SiO_6$	**Actinolite**	$Ca(Mg,Fe)_3(SiO_3)_4$
Acmite	$NaFe'''(SiO_3)_2$	**Hornblende**	$Ca(Mg,Fe)_3(SiO_3)_4$, $CaMg_2Al_2(SiO_4)_3$

Monoclinic		*Monoclinic*	
Spodumene	$LiAl(SiO_3)_2$	**Glaucophane**	$\begin{cases} NaAl(SiO_3)_2 \\ MgSiO_3 \end{cases}$
Jadeite	$NaAl(SiO_3)_2$		
Wollastonite	$CaSiO_3$	**Riebeckite**	$\begin{cases} NaFe'''(SiO_3)_2 \\ FeSiO_3 \end{cases}$
Pectolite	$HNaCa_2(SiO_3)_3$		
Anorthic		*Anorthic*	
Rhodonite	$MnSiO_3$	**Ænigmatite**	
Babingtonite	$\begin{cases} Ca_2Fe(SiO_3)_3 \\ Fe'''_2(SiO_3)_3 \end{cases}$		

It has been shown above that these minerals form two parallel series crystallising in three systems.

The orthorhombic varieties are not very well defined; both enstatite and anthophyllite are liable to an internal decomposition, by which they acquire a pearly or submetallic lustre on the cleavage surfaces, especially on B. The bronzy appearance caused by this change is probably due to very fine films of oxides or hydrates of iron forming in the cleavage cracks, and is an interference effect known as "schiller." The effect is particularly marked in the ferriferous varieties of enstatite known as **bronzite** (or schiller-spath); this mineral is especially characteristic of gabbros and peridotites in which the olivine has often been serpentinised, or in the serpentines derived from such rocks; it was formerly supposed to be a distinct mineral, but is undoubtedly only an altered enstatite; the same change occurs equally in the more ferriferous varieties of $(Mg,Fe)SiO_3$, known as hypersthene. The original "Schiller-spath" (or bastite) from the Harz is so much altered that it practically has the composition of a serpentine. It has been shown by Judd that schillerisation is due to decomposition along solution planes which are usually glide planes.

The **hypersthene** of Labrador is of a dark pinchbeck-brown colour with a peculiar bronzy sheen, and the felspar (labradorite) with which it is associated shows a brilliant play of colours (p. 261). Among the monoclinic pyroxenes, **diallage** is an augite which has suffered the same schillerisation, and closely resembles bronzite in appearance; it is often found interlaminated with bronzite, and is distinguished from it by the oblique extinction. Diallage is the usual pyroxene of gabbro. Among other varieties of pyroxene which deserve mention are two green minerals: "chrome-diopside," which contains a small percentage of Cr_2O_3 and is a conspicuous, though not common, constituent of the "blue ground" at Kimberley; and "omphacite," which is a constituent of eclogite. Both of these may be recognised as pyroxenes by their cleavage and optical properties. A green variety of amphibole known as smaragdite corresponds to omphacite and is often found with it.

Spodumene is an alkali pyroxene, $LiAl(SiO_3)_2$, corresponding in composition to acmite, but differing somewhat widely in form from the other pyroxenes: *mm* $(110):(1\bar{1}0) = 93^\circ\,0'$; $\beta = 69^\circ\,40'$: it possesses not

only a good prismatic cleavage, but an even better "parting" parallel to {100}. It is found in very large white crystals in the granite of Goshen (Massachusetts), and Branchville (Connecticut); but at both localities is much altered. Clear, transparent, yellow crystals come from Brazil, and small crystals of a very beautiful green colour (hiddenite) from Alexander County (North Carolina); one of the most beautiful faceted gems in the British Museum is cut from a clear crystal of the latter.

The parallelism of the pyroxenes and amphiboles is well shown by a comparison of their optical orientation, as illustrated by the annexed diagram, which gives the positions of the indicatrix-axes α and γ for several of them.

PYROXENE GROUP

1. Enstatite. 2. Spodumene. 3. Diopside. 4. Hedenbergite. 5. Augite. 6. Ægirite.

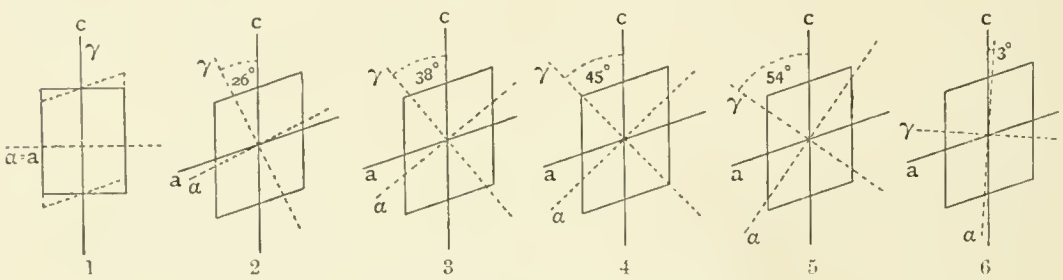

Fig. 575.—Pyroxene Group.

AMPHIBOLE GROUP

1. Anthophyllite. 2. Glaucophane. 3. Tremolite. 4. Hornblende. 5. Arfvedsonite. 6. Riebeckite.

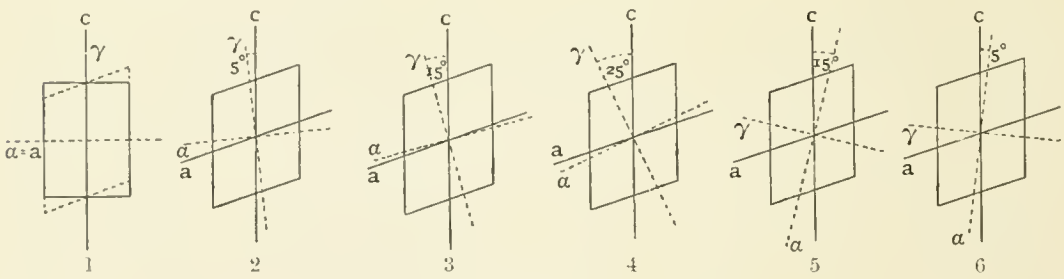

Fig. 576.—Amphibole Group.

In each series there is a gradual rotation of the bisectrices in a counter-clockwise direction in passing from 1 to 6.

Amphibole shows a much greater tendency than pyroxene to appear in fibrous, and even acicular, crystals; the most conspicuous example is the variety known as **asbestos**, which is so fibrous and flexible that it can be woven into cloth, and is very largely used as a non-combustible material for many purposes. In the mica-schist and talc-schist of Lombardy and Turin the best asbestos occurs in fine white silky fibres

sometimes more than a yard in length; a hair-like green asbestos sometimes accompanies the epidote on the fine specimens from the Sulzbachthal. Inferior varieties of shorter and coarser fibre are worked at many other localities; but now the greater part of what is used commercially as "asbestos" is really chrysotile, the fibrous variety of serpentine. "Mountain leather" and "mountain cork" are the names given to matted sheets or nodules of a yellow fibrous amphibole closely allied to asbestos; all these have nearly the composition of tremolite or actinolite.

A blue fibrous mineral from Griqualand, known as "crocidolite," is probably a fibrous riebeckite; by oxidation and partial replacement by silica it becomes converted into a hard, compact, golden-yellow material with fibrous structure and silky chatoyant lustre, much used for ornamental purposes and often called "cat's-eye" or "tiger-eye." This must be regarded as a pseudomorph of quartz after crocidolite.

Another variety of tremolite or actinolite of a totally different appearance is the compact mineral known as **nephrite** or jade. This has a hardness of about $6\frac{1}{2}$, and specific gravity about 3·0; it is one of the toughest of minerals, and has a splintery fracture. On account of its toughness and colour it has always been much prized in ancient times, and weapons and worked articles of jade have been found in many parts of the world. The ancient localities are not known, but it was probably always a rare mineral and found in isolated boulders; it is much worked at the present time in India and China, and also in New Zealand and Alaska. Two varieties are known; the white (which is especially prized in the East) has the composition of tremolite; the green ("greenstone" of New Zealand, etc.) contains more FeO and is regarded as a compact actinolite.

A very similar mineral, generally confused with jade, and equally prized in the East, is the green or white **jadeite**; this is a compact alkali pyroxene, $NaAl(SiO_3)_2$, corresponding in composition to acmite and spodumene; it is tough and has a splintery fracture like that of jade, but is both denser and harder than jade, H = 7, G = 3·3, and it may be distinguished from jade by its readier fusibility. Like jade, the material worked has probably been derived from isolated boulders.

In many rocks pyroxene is altered into amphibole. The name "uralite" (from the original locality) has been given to such crystals, which have the form of pyroxene and the cleavage of amphibole, and the process is named uralitisation; it is exemplified by microscopic crystals in many diabases. Such a change can only take place by a reduction of the proportion of calcium in the pyroxene as compared with magnesium; it is therefore interesting to find that uralite is generally accompanied by calcite or epidote.

Two minerals of some importance are doubtfully referred to the pyroxene group, although they do not possess the characteristic cleavage, namely, wollastonite and pectolite. **Wollastonite** is found in white tabular crystals (tabular spar, Tafel-spath) lining cavities in the ejected blocks of Monte Somma (Mount Vesuvius), associated with

garnet, leucite, etc. It is monoclinic, tabular along {100}, and has a prism angle of 92° 42′; but differs from pyroxene in its perfect cleavages, {100} and {001}, also one parallel to {101}. The mineral is also found in many metamorphic limestones; it has the simple composition $CaSiO_3$.

Pectolite, $HNaCa_2(SiO_3)_3$, is a white mineral found in acicular crystals or fibrous masses of radiating structure, as a secondary product in cavities and veins of several basic rocks; it is monoclinic, and, like epidote, elongated along the axis b; its cleavages are the same as the principal cleavages, AC, of wollastonite, and it is readily fusible (2), and gives off water on heating.

By some authors pectolite is placed among the zeolites, which it certainly resembles in its mode of occurrence; others regard the water as of secondary origin, and suppose the original mineral to have conformed to the pyroxene formula as $(Na_2,Ca)SiO_3$. Compact pectolite is a very tough white material

SECTION XVII

SILICATES (AND TITANATES) OF DIVALENT METALS (*Continued*).

THE PHENACITE GROUP

Dioptase . . .	H_2CuSiO_4
Phenacite . . .	Be_2SiO_4
Willemite . . .	Zn_2SiO_4

The minerals of this group are chiefly interesting as affording examples of the hexagonal-alternating type of symmetry of which dioptase was chosen as type (Fig. 187, p. 74).

Dioptase.—Silicate of copper; H_2CuSiO_4; $CuO = 50{\cdot}4$, $H_2O = 11{\cdot}4$; $SiO_2 = 38{\cdot}2$. Hexagonal; symmetry, hexagonal alternating.

$$a : c = 1 : 0{\cdot}534.$$

$$R = \{100\},\ a = \{10\bar{1}\},\ s = \{70\bar{1}\}.$$

$$RR = (100) : (010) = 84^\circ\ 33',\ Rs = (100) : (70\bar{1}) = 8^\circ\ 12'.$$

Cleavage $\{110\}$, good. Brittle. Fracture, conchoidal. H = 5; G = 3·3. Emerald-green. Streak, green. Lustre, vitreous. Transparent; $\omega = 1{\cdot}667$. Birefringence, strong, positive; $\epsilon - \omega = 0{\cdot}056$. Infusible. Decomposed with gelatinisation by hydrochloric acid.

With the above description compare crystals from the **Khirgis Steppes** (Siberia), Fig. 187, p. 74.

Dioptase is a rare mineral, but attracted attention in 1785 on account of its resemblance to emerald, for which it was at first mistaken. It was made a distinct species by Haüy on account of the hardness, specific gravity, cleavage, and large proportion of copper. He gave it the name dioptase in allusion to the internal glitter which these green translucent crystals exhibit owing to their rhombohedral cleavage cracks (*διά ὀπτάζω* = I see through). By most authors the cleavage rhombohedron $\{110\}$ of 54° 5′, which truncates the edges of R, is taken as $\{100\}$; R then becomes $\{11\bar{1}\}$ (*cf.* Fig. 177). The symmetry is made clear not only by the occurrence of the faces *s* (Fig. 187) on the alternate edges alone of the rhombohedron R, but by the striations on the latter; these are parallel to the edge R*s*, and the faces are also curved in this direction; in fact *s* of Fig. 187 is generally a curved surface ranging from $(11{\cdot}0{\cdot}\bar{1})$ to $(30\bar{1})$.

Dioptase was originally found in beautiful emerald-green crystals and groups lining cavities of a compact limestone, and sometimes accompanied by a little malachite, at Mount Altyn Tübe in the Khirgis Steppes. In 1890 precisely similar crystals, accompanied by chrysocolla and quartz, were brought to Europe from the Mindouli mine in the French Congo.

Since the mineral does not lose weight when heated to 350°, and water is only given off at a red heat, it is regarded not as a hydrated metasilicate but an acid orthosilicate H_2CuSiO_4, and is referred to the same group as phenacite and willemite; these minerals exhibit the same symmetry, and phenacite has an imperfect rhombohedral cleavage; but dioptase is far less closely related to them than they are to each other; their prominent cleavage is the prism, and the rhombohedron angles are—

Phenacite	63° 24′
Willemite	64° 30′
Dioptase	54° 5′ (cleavage)

Phenacite occurs in good, isolated, colourless crystals of habit somewhat similar to that of dioptase, on the amazon-stone of Pike's Peak, and at Mount Antero (Colorado), and has been found in crystals of considerable size in the emerald mines of the Urals, and at Framont in the Vosges. These are sometimes interpenetration twins twinned about the vertical axis. The mineral was named phenacite (φέναξ, a deceiver) on account of its resemblance to quartz; but it possesses a much higher refringence and birefringence, $\omega = 1{\cdot}654$, $\epsilon - \omega = 0{\cdot}015$; it is, therefore, far more suitable for a gemstone when sufficiently clear, and good facetted stones somewhat resemble the diamond.

Willemite has been mentioned above as a zinc ore which accompanies zincite and franklinite at the zinc mines of Franklin Furnace and Sterling Hill in New Jersey, where it occurs mostly as dull, pale yellow cleavable masses; the cleavage is parallel to the base and the hexagonal prism. Crystals are comparatively rare; large flesh-red crystals which owe their colour to a proportion (5 to 12 per cent) of MnO are known as "troostite."

ILMENITE

Ilmenite, $FeTiO_3$ (*Germ.* Titaneisen), as mentioned on p. 356, has generally been classed among the oxides as a member of the hæmatite group. It is an iron-black mineral closely resembling hæmatite in form and habit (rr (100) : (010) = 94° 29′ for ilmenite, and 94° 0′ for hæmatite); and it has a similar conchoidal fracture and submetallic lustre; $H = 5\frac{1}{2}$, $G = 4{\cdot}8$. Well-formed or bright crystals are rare; they differ from hæmatite in their symmetry, which is that of the dioptase group, hexagonal alternating. The mineral is distinguished from hæmatite by a slight but pronounced magnetism (it is, however, not polar like magnetite), and by the titanium; $FeO = 47{\cdot}4$, $TiO_2 = 52{\cdot}6$. It contains Fe_2O_3 and used to be regarded simply as a titaniferous hæmatite

$(Fe,Ti)_2O_3$, or isomorphous mixture of Fe_2O_3 and Ti_2O_3; since, however, some varieties contain magnesia, and in these the ratio (Mg,Fe)O to TiO_2 is always 1 : 1, these varieties must be regarded as isomorphous mixtures of $FeTiO_3$ with $MgTiO_3$; a mineral $MnTiO_3$, known as pyrophanite, is also isomorphous with ilmenite. Platy crystals of ilmenite with triangular striation on the basal planes are common in diabase, and the mineral is a frequent constituent of the more basic rocks. Some of the black heavy sands derived from the decomposition of these rocks consist largely of grains of ilmenite (see also p. 356).

TITANITE

Titanite. — Silicate and titanate of calcium; $CaSiTiO_5$; $CaO = 28{\cdot}6$, $TiO_2 = 40{\cdot}8$, $SiO_2 = 30{\cdot}6$. Monoclinic.

$$a : b : c = 0{\cdot}755 : 1 : 0{\cdot}854. \quad \beta = 60^\circ\ 17'.$$

$A = \{100\}$, $C = \{001\}$, $x = \{102\}$, $l = \{\bar{1}12\}$, $n = \{111\}$, $m = \{110\}$.

ll $(\bar{1}12) : (\bar{1}\bar{1}2) = 46^\circ\ 7'$, Cx $(001) : (102) = 21^\circ\ 0'$, nn $(111) : (1\bar{1}1) = 43^\circ\ 49'$, Cl $(001) : (\bar{1}12) = 40^\circ\ 34'$.

Twinned on A (100). Cleavage $\{110\}$, $\{\bar{1}12\}$, $\{100\}$, imperfect. Brittle. Fracture, sub-conchoidal. $H = 5$; $G = 3{\cdot}5$. Colour, olive-brown. Streak, white. Lustre, adamantine. Transparent; $\beta = 1{\cdot}894$. Birefringence, very strong, positive; $\gamma - \alpha = 0{\cdot}121$. Axial plane (010). Acute bisectrix nearly normal to x (102). $2E_{Na} = 52\frac{1}{2}^\circ$. Dispersion very strong, inclined; $\rho > v$; $2E_\rho = 57^\circ$; $2E_v = 47^\circ$ about. Fusible (3). Decomposed by hydrochloric acid.

With the above description compare crystals from **Pfitschthal** (Tyrol).

Titanite, or sphene, is a common constituent of many igneous rocks, and is therefore of petrographical importance, although it only occurs sparingly and in small crystals; the large crystals to be seen in collections are found in gneiss, in chloritic schists, or in crystalline limestones. The crystals are usually angular in appearance (hence the name from $\sigma\phi\acute{\eta}\nu$, a wedge).

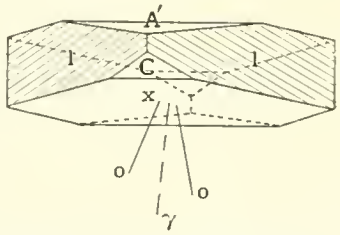

Fig. 577.—Titanite, C $\{001\}$, x $\{102\}$, A $\{100\}$, l $\{\bar{1}12\}$.

The habit is extremely variable, and the combination here figured is only one of many; different authors place the crystallographic axes in different positions. Fig. 577 is turned so as to correspond to the upper part of the large twinned crystal in Fig. 578; such twins are very characteristic. A (100) is the twin plane and the individuals are sometimes juxtaposed, as in Fig. 578, but sometimes interpenetrant; they may then give rise to cruciform groups where such forms as s $\{021\}$ or n $\{111\}$ are predominant. A parting parallel to $\{221\}$ appears to be due to lamellar twinning on that face, and the crystals are striated parallel to the same plane. The striations on l $\{\bar{1}12\}$, which are parallel to its intersections with C, and those on A (parallel to edge Am) sometimes help one to recognise the forms on this complicated mineral.

Titanite is most easily recognised by its strong inclined dispersion, which in ordinary sections converts the hyperbola into fringes of red and blue light, and its apices into patches of white light; in rock sections the mineral is recognised by this feature and by its high relief; the birefringence is very strong. The dispersive power is very

Fig. 578.—Titanite twinned on (100), with Adularia, from Switzerland.

marked; $\beta = 1{\cdot}884$ for lithium light, and $1{\cdot}904$ for thallium light. This and its other optical properties would render it a valuable gemstone if the hardness were greater; with the exception of the diamond, no facetted mineral possesses a more beautiful fire than sphene.

Fig. 578 represents large pale green twins associated with adularia in a mica-schist from St. Gothard.

The colour of titanite varies through different shades of brown, yellow, green, and pink; and the lustre is often somewhat resinous; the wide range of colour is doubtless due to the varying proportions of iron and manganese which the mineral contains. The colour is altered on heating.

The large crystals found in crystalline limestones, as in Canada and New York, are usually deep brown or black in colour; some of these are tabular owing to the predominance of the faces C.

One of the alteration products of ilmenite (known as leucoxene) appears to be largely a white earthy titanite.

HEMIMORPHITE

Hemimorphite.—Silicate of zinc; $H_2Zn_2SiO_5$; $ZnO = 67{\cdot}5$, $H_2O = 7{\cdot}5$, $SiO_2 = 25{\cdot}0$. Orthorhombic; symmetry, polar.

$$a : b : c = 0{\cdot}783 : 1 : 0{\cdot}478.$$

$B = \{010\}$, $C = \{001\}$, $m = \{110\}$, $t = \{301\}$, $s = \{101\}$, $e = \{011\}$, $e' \{01\bar{1}\}$, $v = \{12\bar{1}\}$.

$mm\ (110) : (1\bar{1}0) = 76^\circ\ 9'$, $Cs\ (001) : (101) = 31^\circ\ 23'$, $Ct\ (001) : (301) = 61^\circ\ 20'$, $Bv\ (010) : (12\bar{1}) = 50^\circ\ 47'$, $Be\ (010) : (011) = 64^\circ\ 28'$.

Twins on (001). Cleavage m {110}, perfect; s {101}, C {001}, imperfect. Brittle. Fracture, uneven. $H = 5$; $G = 3{\cdot}4$. Colourless. Streak, white.

Lustre, vitreous. Transparent; $\beta = 1{\cdot}617$. Birefringence, strong, positive; $\gamma - \alpha = 0{\cdot}022$. Axial plane (100). Acute bisectrix normal to C (001); $2E = 78^\circ\ 30'$. Dispersion, strong; $\rho > v$. Fusible with difficulty (6). Decomposed by hydrochloric acid. Pyro-electric.

With the above description compare crystals from **Altenberg** (Aachen).

Hemimorphite or calamine (*Germ.* Galmei, Kieselzinkerz) was known long ago as a zinc ore, but no distinction was made between the silicate and carbonate; the names calamine and smithsonite have been applied to both, and hemimorphite, a name recalling the most interesting feature of this mineral, was introduced in order to avoid the confusion. The polar character of the mineral is well shown by the glassy crystals from the old zinc mines of Altenberg, which line cavities in a compact ore consisting of the silicate and carbonate; they are generally attached by the antilogous pole, the lower end of Fig. 579; the face B is vertically striated. The pyro-electric property is easily studied, as described on p. 116, by Kundt's method; simple crystals become covered, while cooling, with the red lead at the analogous end, and with yellow sulphur at the more acute antilogous end. Supplementary twins like those of Figs. 232 and 233 attract the red lead at both their ends, and show a band of yellow sulphur in the middle where the two antilogous ends meet. The mineral used to be known as "electric calamine." That it is to be regarded as a basic and not a hydrated silicate, is indicated by the fact that the crystals remain unchanged up to 340°, and only give up their water at a red heat.

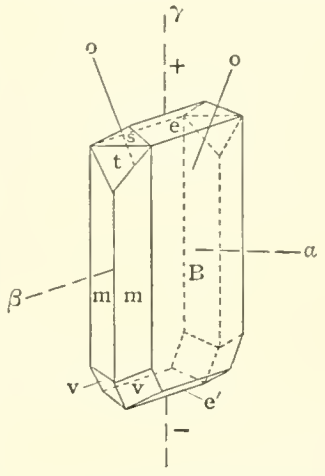

Fig. 579.—Hemimorphite, B {010}, *m* {110}, *e* {011}, *s* {101}, *t* {301}, *e'* {01$\bar{1}$}, *v* {12$\bar{1}$}.

TALC AND SERPENTINE

Talc.—Silicate of magnesium; $H_2Mg_3(SiO_3)_4$; $MgO = 31{\cdot}7$, $SiO_2 = 63{\cdot}5$; $H_2O = 4{\cdot}8$. Monoclinic (?). Cleavage, pinakoidal {001}, perfect. Sectile. Pliable. $H = 1$; $G = 2{\cdot}7$. Colour, silvery-white. Streak, white. Lustre, pearly. Translucent; $\beta = 1{\cdot}55$. Birefringence, negative, strong; $\gamma - \alpha = 0{\cdot}040$. Acute bisectrix normal to the cleavage; $2E = 19^\circ$. Almost infusible. Insoluble in acids. Feel, greasy.

With the above description compare crystallised material from **St. Gothard**.

Serpentine.—Silicate of magnesium; $H_4Mg_3Si_2O_9$; $MgO = 43{\cdot}5$, $SiO_2 = 43{\cdot}5$, $H_2O = 13{\cdot}0$. Massive. Fracture, splintery. $H = 3$; $G = 2{\cdot}6$. Green. Streak, white. Lustre, greasy. Translucent; $\beta = 1{\cdot}57$. Birefringence, negative, weak; $\gamma - \alpha = 0{\cdot}010$. Fusible with difficulty (6). Decomposed by hydrochloric acid.

With the above description compare massive material from the **Lizard** (Cornwall).

These two magnesian silicates may be considered together; they are the common decomposition products of ferro-magnesian silicates, and

are usually of secondary origin. Both minerals occur in large masses; talc as talc-schist (*e.g.* at the St. Gothard), when it is associated with chlorite, serpentine, dolomite, magnesite, etc.; serpentine as an alteration product of peridotites and other olivine rocks (*e.g.* at the Lizard, Cornwall).

Talc in the foliated silvery varieties is fairly pure, and shows a hexagonal outline; the crystals, like those of mica and chlorite, are probably monoclinic. The soft, greasy, pliable cleavage flakes are easily recognised. The interference figure yielded by a flake of talc resembles at first sight a uniaxial figure, but is in reality biaxial with a very small angle; in this respect and in the strength of the birefringence it might be confused with a cleavage flake of phlogopite; but talc may be distinguished from any mica by its softness and pliability; the birefringence is stronger than that of a chlorite. The percussion figure is a three- or six-rayed star, one ray of which is parallel to the axial plane.

Many varieties of talc are coloured, and such usually contain from 1 to 4 per cent of FeO; they may have various shades of yellow, green, or red.

Talc is known not only in foliated masses, but also as the quite compact, structureless variety named "steatite"; this soft, white, or coloured, greasy mineral is also called "soapstone," and, under the name "French chalk," is used by tailors. Much of the white or gray material veining serpentine is steatite. Very remarkable and perfect pseudomorphs of steatite after quartz are found at Göpfersgrün in Bavaria; their origin is difficult to understand, but a similar magnesium silicate can be artificially produced by the action of magnesian solutions upon silica; with these crystals are also found pseudomorphs of the steatite after rhombohedra of dolomite.

Serpentine, even when apparently quite compact, always shows a fibrous structure in thin sections under the microscope, and the fibres have a positive extension; the large masses of the Lizard and similar localities, which are really altered rock masses, present little or no visible structure, contain a considerable proportion of FeO, and are by no means a pure mineral; the colour varies through different shades of green, red, and yellow, and is commonly a leek-green. The white streak of all these varieties is characteristic. A variety known as "antigorite" has a platy structure, and shows a more definite interference figure; the typical specimens come from the Antigorio Valley in Piedmont. Where the mineral fills veins or constitutes seams in massive serpentine it has a well-marked fibrous structure, the fibres being transverse to the veins, and is a somewhat purer mineral. This fibrous variety with silky lustre is known as "chrysotile." Most of the material known as "asbestos" in the trade is in reality chrysotile, which is worked on an enormous scale in the metamorphic region of Megantic County and Beauce County in the province of Quebec; it serves all the purposes for which asbestos is used, although the chrysotile fibres are not so long nor so silky as those of true asbestos. Its infusibility and bad conductivity for heat fit it for incombustible fabrics and paints, firemen's gloves, packing for steam tubes, etc.

The manner in which, on a microscopic scale, the olivine of rocks becomes serpentinised by transformation into chrysotile along its cracks, and the large pseudomorphs of yellow serpentine after olivine found at Snarum, which were originally supposed to be serpentine crystals, have been mentioned on p. 416.

Both talc and serpentine are to be regarded as basic and not hydrated silicates, since they only part with their water at a high temperature. The massive serpentine used so largely for decorative purposes, and often known as "serpentine marble," derives much of its beauty and variety from the veins and patches of white magnesite and talc which it contains, and from splashes of blood-red iron-stained serpentine; the more soluble constituents of the rocks from which it has been derived furnish veins of dolomite, calcite, and opal. The original pyroxene of the rock is often represented by the schiller spar described on p. 429. The celebrated "verde antique" is a serpentine breccia.

Some very remarkable pseudomorphs of considerable size have been found at the Tilly Foster Iron Mine, Brewster, New York; these consist of pale green serpentine with a perfect cubic cleavage. Some have thought them to be pseudomorphs after the oxide of magnesium, periclase, which is known in small cubic crystals; others regard them as true crystals of serpentine. They are accompanied by serpentine pseudomorphs after calcite, enstatite, hornblende, etc.

Both serpentine and steatite have been much used for ornamental purposes from early times; although very soft they are, like other decomposition products, the last results of a series of changes and are, therefore, not liable to further decay. Some of the very earliest worked articles known consist of steatite; the coloured varieties (pink and yellow) of this mineral are much used for ornaments by the Chinese at the present day.

Chrysocolla, $CuSiO_3 . 2H_2O$ (?), is the only other silicate of the divalent metals sufficiently common to merit notice. It is a compact amorphous mineral with a lustre like that of opal; the colour is green, blue, or brown; the impure varieties are black, but the streak is whitish. It is a common decomposition product of copper minerals, and a dark impure chrysocolla known as "pitchy copper ore" (kupferpecherz) is a well-known ore of copper.

We next pass to a small group of minerals which are silicates (titanates or zirconates) of divalent with monovalent elements. Of these apophyllite is the only one which is at all common. Clearly, however, some of the minerals considered above, which contain hydrogen, such as dioptase, hemimorphite, chrysocolla, talc, and serpentine, may be regarded as belonging to this group in a strict classification.

Apophyllite. — Hydrated silicate of calcium and potassium; $(H,K)_2Ca(SiO_3)_2 . H_2O$ (?). $K_2O = 5{\cdot}3$, $CaO = 25{\cdot}3$, $SiO_2 = 54{\cdot}2$, $H_2O = 15{\cdot}2$ (if $H : K = 7 : 1$). Pseudo-tetragonal.

$$a : c = 1 : 1{\cdot}2515.$$
$$C = \{001\},\ A = \{100\},\ p = \{111\}.$$
$$Ap\ (100) : (111) = 52^\circ\ 0',\ Cp\ (001) : (111) = 60^\circ\ 32'.$$

Cleavage C $\{001\}$, perfect; m $\{110\}$, imperfect. Brittle. Fracture, uneven. $H = 4\frac{1}{2}$; $G = 2{\cdot}3$. Colourless. Streak, colourless. Lustre, vitreous. Transparent; $\omega = 1{\cdot}53$. Birefringence, positive, weak; $\epsilon - \omega = 0{\cdot}002$. Easily fusible ($1\frac{1}{2}$). Decomposed by hydrochloric acid.

With the above description compare crystals from **Andreasberg** (Harz).

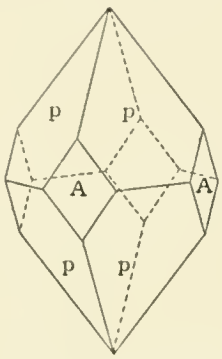

Fig. 580.—Apophyllite, p {111}, A {100}.

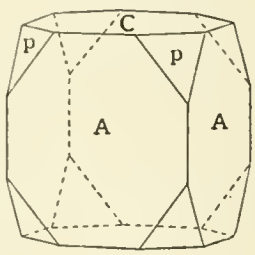

Fig. 581.—Apophyllite, A {100}, C {001}, p {111}.

Apophyllite is often classed among the zeolites, for it exfoliates and gives off water at a comparatively low temperature, and is commonly a mineral of secondary origin found like them in amygdaloidal cavities of basalt. The minerals classed together below as zeolites are, however, all aluminiferous silicates (p. 483), and part readily with their water; apophyllite gives off little, if any, of its water at 100°, and only about half of it at 250°. A certain proportion of the water—it is not certain exactly how much—is reabsorbed again in a moist atmosphere, and is therefore regarded as water of crystallisation; this is represented by H_2O in the above formula.

The chief interest of apophyllite lies in its optical peculiarity. Brewster found in 1818 that some varieties give quite a peculiar interference figure in white light; the rings do not present the colours of Newton's orders, but may consist of violet, greenish-yellow, and white circles, alternating, without any tint of red; or, as was found by Herschel, in one variety the rings are only white and black; the latter variety he called "leucocyclite." Now the true sequence of colours of Newton's rings is only given by crystals in which the birefringence does not alter with the wave length; if this is not the case the colours are different. In some apophyllite the birefringence for red light is about 0·002, for sodium light about the same; but other varieties of the mineral are positive for some colours, isotropic for another, and negative for others. Another explanation is suggested by the fact that the apophyllite rings may be imitated by a combination of a uniaxial positive with a uniaxial

negative crystal. It is therefore possible that the peculiarities of apophyllite may be due to its being an isomorphous mixture of a positive with a negative substance; the leucocyclite is positive, and since heating to 275° changes the rings of ordinary apophyllite to the leucocyclite type, it seems to be a less hydrated silicate. In addition to these peculiarities of the uniaxial interference figure, many apophyllites show in basal section a partition into sectors, some of which are biaxial, negative for blue, and positive for red, with the axial planes crossed as in brookite.

It is, therefore, clear that apophyllite is an intergrowth of two or more silicates which differ in their optical properties. The chemical composition of the mineral is by no means certain; it contains fluorine.

Some Noteworthy Localities:

Andreasberg (Harz).—Colourless or pink glassy crystals of pyramidal habit, forms A*p*, were found as a vein-mineral accompanying calcite, galena, arsenic and arsenical ores; these are generally without the basal plane (Fig. 580). The faces A {100} are vertically striated.

Poonah (Bombay).—Large white and greenish crystals of tabular habit, with large basal pinakoid (Fig. 581), were found during the construction of the Bombay and Poonah railway in amygdaloidal cavities of the Deccan trap, associated with pale pink stilbite, scolecite and analcite.

SECTION XVIII

THE SILICATES OF ALUMINIUM

TOPAZ

Topaz. — Fluoriferous silicate of aluminium; $(AlF)_2SiO_4$; $Al_2O_3 = 55{\cdot}44$, $SiO_2 = 32{\cdot}61$, $F = 20{\cdot}65$. Orthorhombic; symmetry, polar (?).

$$a : b : c = 0{\cdot}528 : 1 : 0{\cdot}477.$$

$C = \{001\}$, $m = \{110\}$, $l = \{120\}$, $o = \{221\}$, $u = \{111\}$, $i = \{223\}$, $d = \{201\}$, $f = \{021\}$, $y = \{041\}$, $n = \{140\}$.

$mm\ (110) : (1\bar{1}0) = 55^\circ\ 43'$, $ll\ (120) : (1\bar{2}0) = 86^\circ\ 49'$, $Co\ (001) : (221) = 63^\circ\ 54'$, $Cu\ (001) : (111) = 45^\circ\ 35'$, $Ci\ (001) : (223) = 34^\circ\ 14'$, $Cy\ (001) : (041) = 62^\circ\ 20'$, $Cf\ (001) : (021) = 43^\circ\ 39'$, $uu\ (111) : (1\bar{1}1) = 78^\circ\ 20'$.

Cleavage C $\{001\}$, perfect. Brittle. Fracture, sub-conchoidal. $H = 8$; $G = 3{\cdot}5$. Pale yellow. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1{\cdot}618$, $\gamma = 1{\cdot}623$. Birefringence, positive, weak; $\gamma - \alpha = 0{\cdot}011$. Axial plane (010). Acute bisectrix normal to C (001); $2E = 114^\circ$. Dispersion, strong; $\rho > v$. Infusible. Decomposed with difficulty by sulphuric acid.

With the above description compare crystals from **Schneckenstein** (Saxony).

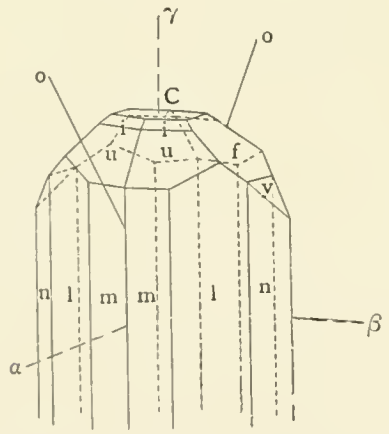

Fig. 582.—Topaz, m {110}, l {120}, n {140}, u {111}, i {223}, y {041}, f {021}, C {001}.

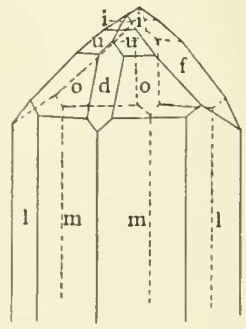

Fig. 583.—Topaz, m {110}, l {120}. o {221}, d {201}, u {111}, i {223}, f {021}.

Topaz is of interest as one of the fluoriferous silicates found commonly in those veins of granite or gneiss which are supposed to have been filled

by the action of fluoriferous vapours, and often contain cassiterite (see p. 361); in these veins topaz is accompanied by tourmaline, apatite, mica and fluor. Topaz is one of those finely crystallised minerals which must have attracted attention in early times; its name is the "topazius" of Pliny, but this evidently refers to a different mineral, probably to chrysolite, since he derives the word from an island in the Red Sea. On the other hand, the Roman "chrysolithus" was probably our topaz.

The hardness, high refractive index, and variety of colour, render topaz valuable as a gemstone.

The crystals can usually be recognised and orientated by the perfect basal cleavage and the vertical striation of the prism faces. In the Schneckenstein crystals (Fig. 582) the basal plane is sometimes larger than as shown in the figure, and the other forms are only small faces on its edges. Doubly terminated crystals are rare; this we have already seen to be the case with the pyro-electric mineral hemimorphite, and most topaz crystals seem to be pyro-electric in the direction of the vertical axis; the symmetry is therefore probably polar. Some doubly terminated crystals become similarly electrified at the two ends, and may be twins, like those of hemimorphite (Fig. 233). On the other hand, both natural and artificial etched figures appear to accord with holosymmetry.

The axial angle is so large that the optic axes are rarely visible on the edges of the field of view of the microscope with oil immersion; the interference figure, with its positive bisectrix normal to the plate, is beautifully seen through a cleavage flake. The optic axial angle varies considerably in different specimens. Penfield has shown that the mineral always contains a little water, and that the axial angle 2E diminishes from 127° to 84° as the proportion of water increases from 0·2 to 2·5 per cent; at the same time the proportion of fluorine decreases from 20 to 16 per cent. The water found in the analyses is, therefore, due to the partial replacement of F by OH in the formula given above. The value $2E = 114°$ given above corresponds to 0·93 per cent of water. It is not known for certain to what the colour is due; the Schneckenstein crystals are mostly pale yellow, but some are colourless, as are also crystals from Japan and Mexico (Fig. 583); the Brazilian crystals are brown; large crystals from the Urals (Fig. 584) are deep wine-yellow; many of those from Adunchilon are pale blue. Most of the brown crystals turn to rose-red on heating, and Brazilian topazes are sometimes treated in this way before being cut as gems; some of the yellow varieties lose their colour altogether when heated.

Topaz often contains microscopic cavities filled with liquids; one of these has received the name "brewsterlinite," because it was investigated by Brewster, who found it to have the low refractive index 1·2; they appear to be, at least in part, impure carbon dioxide.

Some Noteworthy Localities:

Schneckenstein (near Auerbach, in Saxony).—Cavities in the so-called "Topasfels," which is a brecciated mass of tourmaline-quartz rock cemented by topaz and quartz, are lined with crystals of topaz (Fig.

582), sometimes associated with cassiterite, apatite, and chalcopyrite. With these is usually a white or yellowish earthy kaolin.

Russia.—Several localities on the Urulga River in the Nerchinsk district, Siberia, have afforded fine topaz crystals in the druses of granite; the best are perhaps the pale blue crystals found at Adunchilon (like Fig. 585), with smoky quartz, beryl, and orthoclase.

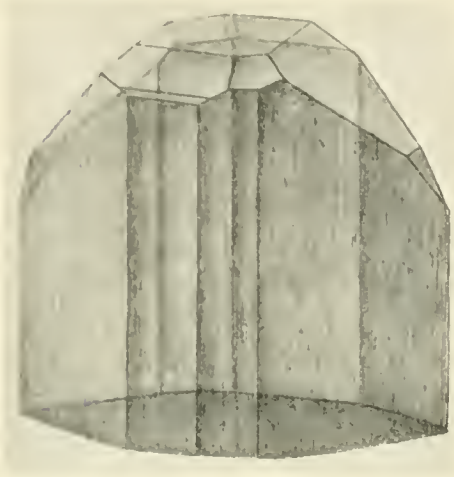

Fig. 584.—Topaz from Urulga River.

Fig. 584 represents one of the six enormous pale brown crystals from the Urulga River which are preserved under cover in the British Museum, since it is believed that these lose their colour when exposed to daylight.

Large blue crystals, characterised by the large basal plane, from the granite of Mursinka in the Urals, are associated with smoky quartz, lepidolite, orthoclase, and masses of tabular albite crystals (Fig. 583).

Brazil.—The Brazilian crystals in mineral collections are generally separated from the matrix, since in Minas Geraes, where they are found in large quantities, they occur in a soft talc schist, or in pockets of kaolin, with quartz, rutile, etc. Sometimes the topaz is enclosed or partially enclosed in quartz. The crystals are deep brown, and somewhat resemble Fig. 582 in habit, except that they have no basal plane.

Japan.—Colourless crystals of the habit shown in Fig. 583 are found in stanniferous sands, with other minerals derived from the decomposed granite of the Kiso Range, in Mino province.

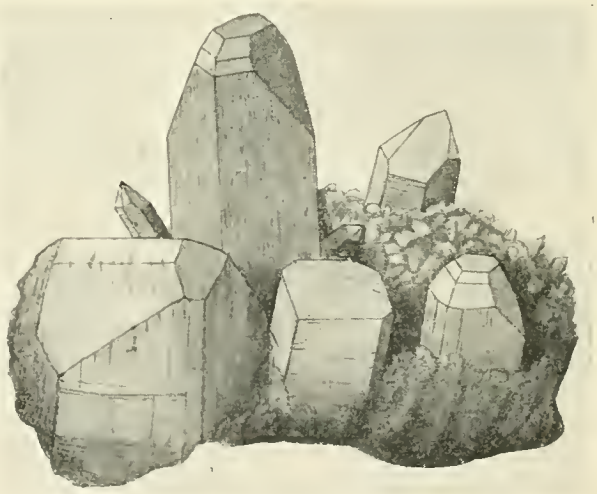

Fig. 585.—Topaz, with Quartz and Orthoclase, from Alabaschka (Urals).

Crystals of a similar acute habit are found in the stanniferous sands of **Durango** in Mexico, where they have been derived from a trachyte. Somewhat similar crystals are found in rhyolite at San Luis Potosi, and this occurrence closely resembles that of Nathrop in Colorado, where similar limpid crystals are found in druses of the rhyolite with quartz, sanidine, and a dark-coloured manganese garnet.

ANDALUSITE AND CYANITE

Andalusite. — Silicate of aluminium; Al_2SiO_5; $Al_2O_3 = 63$, $SiO_2 = 37$. Orthorhombic.

$$a : b : c = 0{\cdot}986 : 1 : 0{\cdot}702.$$
$$C = \{001\},\ m = \{110\}.$$
$$mm\ (110) : (1\bar{1}0) = 89^\circ\ 10'.$$

Cleavage $\{110\}$. Brittle. Fracture, uneven. $H = 7\frac{1}{2}$; $G = 3{\cdot}1$. Reddish-brown. Streak, colourless. Lustre, vitreous. Translucent; $\beta = 1{\cdot}638$. Birefringence, negative; $\gamma - \alpha = 0{\cdot}011$. Axial plane (010). Acute bisectrix normal to C; $2H = 96^\circ\ 30'$. Pleochroic; β and γ olive-green, α dark blood-red. Infusible. Insoluble in acids.

With the above description compare crystals from **Morbihan** (Brittany).

Cyanite.—Silicate of aluminium; Al_2SiO_5; $Al_2O_3 = 63$, $SiO_2 = 37$. Anorthic.

$$a : b : c = 0{\cdot}899 : 1 : 0{\cdot}697.$$
$$C = \{001\},\ A = \{100\},\ B = \{010\},\ m = \{110\},\ l = \{1\bar{1}0\}.$$
$$CB\ (001) : (010) = 86^\circ\ 36',\ CA\ (001) : (100) = 79^\circ\ 10',\ AB\ (100) : (010) = 73^\circ\ 39',$$
$$Am\ (100) : (110) = 48^\circ\ 30',\ Al\ (100) : (1\bar{1}0) = 34^\circ\ 13'.$$

Cleavage $\{100\}$, perfect; $\{010\}$, imperfect. Brittle. Fracture, somewhat fibrous. H (on A) = 7 parallel to edge AC, $4\frac{1}{2}$ parallel to edge AB. $G = 3{\cdot}6$. Blue to white. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1{\cdot}72$. Birefringence, negative, rather strong; $\gamma - \alpha = 0{\cdot}016$. Axial plane inclined at 30° to the edge AB. Acute bisectrix nearly normal to A; $2H = 100^\circ$. Infusible. Insoluble in acids.

With the above description compare crystals from **St. Gothard.**

Andalusite and cyanite possess the same percentage composition; and this belongs also to a third mineral distinct from both, namely sillimanite or fibrolite.

Andalusite is found in schists which are the result of the metamorphic action of granite and similar rocks. The best known specimens are the large crystals found in the argillaceous schist at Rohan in Morbihan (Brittany). These are large uneven prisms, generally much altered, and partly converted into kaolin. Very similar are the specimens from Lisens Alp in the Tyrol (Fig. 586). The unaltered mineral is found in Minas Geraes (Brazil), as water-worn crystals, which show the remarkable dichroism by appearing green or red according to the direction in which they are viewed; gemstones cut from this mineral

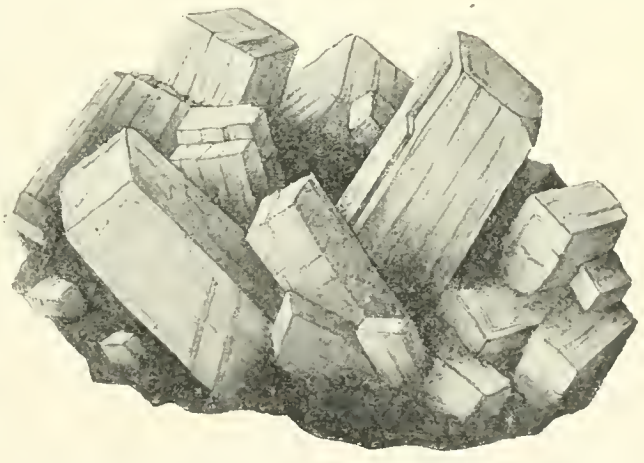

Fig. 586.—Andalusite on Mica Schist, from Lisens Alp (Tyrol).

display a beautiful effect for the same reason, if so facetted that the light obliquely reflected from the sides is differently coloured from the light more directly refracted in the centre.

The Morbihan crystals belong to the variety known as "chiastolite," from the Greek letter χ (χιάζω), on account of its black carbonaceous enclosures, which appear as a cruciform design when the crystals are cut across (Fig. 587). The disposition of this black material within the crystal is very curious; the various patches are wedge-shaped, becoming thinner towards one end of the crystal and thicker towards the other; the central core is sometimes hour-glass-shaped, becoming thicker from the centre towards both ends; this peculiar structure of chiastolite is supposed to indicate a skeletal growth of the crystals, in which the carbonaceous residue has followed the lines of growth during the conversion of the slate into crystals of andalusite. These crystals were known as "macles" in very early times, and the origin of the name is supposed to be the heraldic term macula, used for the heraldic lozenge; it is believed that this device may have been introduced into their armorial bearings by the family of the Vicomte de Rohan to represent the chiastolite of their neighbourhood.

Fig. 587.—Chiastolite from Massachusetts.

Cyanite, or disthene, is a mineral of very different appearance; its properties are best studied in the pale blue blade-shaped crystals which accompany staurolite in a white paragonite- (mica) schist at Monte Campione near St. Gothard in Switzerland. The cyanite and staurolite are sometimes united in regular position, as described on p. 86 (Fig. 219). The extraordinary difference of the hardness in different directions (p. 111) was discovered by Haüy, who gave the mineral the name disthene (δίς and σθένος, double strength); it can easily be tested by scratching a crystal with a knife; the other name, cyanite, refers to the blue colour.

Both andalusite and cyanite when raised to a high temperature (about 1350° C.) become converted into an aggregate of fibres which give straight extinction, have a uniform hardness of $6\frac{1}{2}$, and a specific gravity of 3·2, the chemical composition remaining unchanged. These properties show the resulting product to consist of sillimanite, a fibrous mineral found in gneiss and schists, especially those which contain cordierite.

The compact sillimanite known as fibrolite has often been used in the manufacture of prehistoric implements and ornaments; it is sometimes wrongly called jade.

The differences in constitution between the above three minerals have not yet been established. Groth has suggested that the more stable compound, cyanite, is a metasilicate $(AlO)_2SiO_3$, and the less stable andalusite an orthosilicate $Al(AlO)SiO_4$; just as enstatite is more stable than olivine among the magnesian silicates.

THE CLAYS

Corresponding to the scaly talc and the amorphous steatite among the magnesian silicates, are the family of scaly and amorphous minerals known as clays among the aluminous silicates. The most important of these is **kaolinite** or china clay, the almost universal decomposition product of felspar. For commercial purposes, for the manufacture of porcelain and china, it is worked on a large scale in certain decomposed granites; for example at St. Austell in Cornwall, where it occurs in vast masses associated with tourmaline-quartz rock; the name is of Chinese origin, like the industry for which the mineral is worked. The silvery-white powder found at Amlwch in Anglesey is seen under the microscope to consist entirely of minute hexagonal plates with perfect basal cleavage, which belong to the monoclinic system. This and other pure white specimens of kaolinite have the composition $H_4Al_2Si_2O_9$, corresponding exactly to serpentine, $H_4Mg_3Si_2O_9$; but much kaolinite is coloured yellow or brown and is impure, containing ferric oxide or hydrate. Common clay is generally a mixture of kaolinite with many decomposition products, partly other hydrated aluminous silicates; and many such compounds have been distinguished by special names. The plasticity of clay and its impermeability to water, qualities which make it so important, may be partly due to its minutely scaly texture, and its unctuous feel is due to the same cause. Most clays can be recognised by the peculiar earthy odour which they yield when breathed upon.

"Lithomarge" (*Germ.* Steinmark) is a compact kaolinite which sometimes resembles steatite in appearance, but has not the same greasy feel. The variously coloured material used by the Chinese for ornaments and images, and consequently named agalmatolite, is really of two sorts; some is steatite, and some is a compact aluminous silicate having the composition $H_2Al_2(SiO_3)_4$; the latter corresponds to a member of the clay family named pyrophyllite, which is sometimes found in radially grouped foliated masses consisting of cleavable biaxial crystals.

Kaolinite is a decomposition product of many aluminous silicates, and is consequently found as a pseudomorph after several minerals, *e.g.* albite, orthoclase, leucite, beryl; but it is not found as a result of the alteration of anorthite.

SECTION XIX

THE ALKALINE SILICATES

LEUCITE

Leucite.—Silicate of potassium and aluminium; $KAl(SiO_3)_2$; $K_2O = 21{\cdot}58$, $Al_2O_3 = 23{\cdot}40$, $SiO_2 = 55{\cdot}02$. Pseudo-cubic. Common form, icositetrahedron $\{2\bar{1}1\}$. Cleavage, dodecahedral, very imperfect. Brittle. Fracture, conchoidal. $H = 5\frac{1}{2}$; $G = 2{\cdot}5$. Colourless. Streak, white. Lustre, vitreous. Transparent; $\beta = 1{\cdot}508$. Birefringence very weak. Infusible. Decomposed by hydrochloric acid.

With the above description compare crystals from **Vesuvius.**

Leucite is noteworthy as one of the minerals which have contributed most to our knowledge of pseudo-symmetry. Although crystallising in the most perfect icositetrahedra $\{211\}$ (the leucitohedron), it was found by Brewster to be birefringent and even biaxial in parts; the peculiarity was at first attributed to a lamellar structure. As described on p. 184, it was first shown by vom Rath that the angles are not those of the cubic icositetrahedron, and that it is traversed by twin lamellæ parallel to (101) and (011), so that the mineral was described as tetragonal. In accordance with this view the upper face (112) is more readily attacked by solvents than the lower faces (211) and (121). Since, however, it has been found that the twin lamellæ are also parallel to (110) and $(\bar{1}10)$, and that the crystals consist of overlapping biaxial material, the mineral is regarded as either orthorhombic or monoclinic; the appearance presented by thin sections parallel to (001) and (111) is shown in Figs. 370, 371. In some crystals a positive bisectrix with a small axial angle emerges *normal* to each cube face, and this indicates orthorhombic rather than monoclinic symmetry.

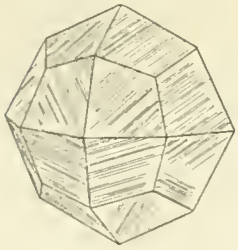

Fig. 588. — Leucite, showing Twin Striations.

It was shown by Klein that when a leucite section is heated to 433° between crossed nicols a dark shadow seems to extend across the plate, which then becomes isotropic; on cooling, the twin lamellæ reappear. Rosenbusch showed that at the above temperature the inequalities of the crystal faces due to the minute facets of the twin lamellæ also disappear,

and the faces become smooth and bright (p. 186). There can be little doubt, therefore, that at high temperatures the mineral really belongs to the cubic system. It has therefore been suggested that it crystallised at a high temperature as a cubic mineral and broke up into orthorhombic sectors on cooling.

Leucite generally contains abundant inclusions of other minerals which are situated in regular lines following the contour of the crystal and not influenced by the optical boundaries:—another argument in favour of the above view.

The double refraction is so slight (not more than 0·001) that in thin sections leucite may appear isotropic, but the twin lamellation is generally discernible and betrays the birefringence of the mineral.

By treatment with solution of sodium chloride or carbonate, Lemberg has succeeded in converting leucite into analcite, the corresponding hydrated sodium compound, whose formula differs from that of leucite by containing one molecule of water; and by treatment with fused sodium chloride it is converted into an (anhydrous) sodium leucite. Leucite is, in fact, an unstable compound, and as found in nature is usually white and opaque owing to conversion into analcite, or ultimately into kaolin. The name is derived from λευκός, white.

Some Noteworthy Localities: .

Vesuvius.—Porphyritic crystals altered in this manner are found in the old lavas of Vesuvius, where they are accompanied by porphyritic augite and orthoclase in a gray porous ground-mass; small clear transparent crystals are sometimes found in the modern lava, or fall like a shower of hailstones in an eruption; clear crystals are also found with meionite and sanidine in the ejected dolomite blocks.

Some of the lavas of **Capo di Bove** near Rome, of the **Eifel**, and of the **Kaiserstuhl** in Baden, consist almost entirely of leucite and augite.

NEPHELINE

Another alkaline silicate often associated with leucite in the group of alkaline rocks (phonolite, tephrite, leucite-basalt, etc.), is **nepheline**, which has a composition nearly represented by the formula $K_2Na_6Al_8Si_9O_{34}$. Glassy, colourless, or white hexagonal prisms of nepheline are found in druses of the ejected blocks of Monte Somma, usually accompanied by sanidine, or by garnet, mica, and hornblende. They belong to the hexagonal system, have a fair prismatic and basal cleavage, and possess weak, negative double refraction: $H = 5\frac{1}{2}$, $G = 2{\cdot}6$. Etching with hydrofluoric acid produces similar, unsymmetrical figures upon the six prism faces, showing that the mineral possesses only a polar axis of hexagonal symmetry, and belongs to Class XIV. of pp. 280-81; it is the only representative of this class among minerals; the crystals are usually, however, supplementary twins and simulate holosymmetry. Nepheline possesses nearly the same specific gravity, refractive power, and birefringence as quartz, and in thin sections is only to be distinguished from quartz by the sign of the birefringence. From apatite, which it resembles in this

respect, it is distinguished by its lower refractive index, which is almost the same as that of Canada balsam.

Nepheline, like leucite, is far from stable, and many of the porphyritic crystals found in soda-bearing rocks, especially older plutonic rocks, are called elæolite (from ἔλαιον, oil) on account of their greasy lustre, which is probably due to incipient alteration; they generally contain more water than glassy nepheline.

The elæolite-syenite of Southern Norway contains large, opaque, gray hexagonal prisms of the mineral associated with orthoclase, oligoclase, augite, ægirite, etc. Even among the Vesuvian specimens are to be found white hexagonal prisms of opaline lustre, which have been regarded as distinct minerals, and have been named "davyne" and "cavolinite"; these seem to be really altered nepheline.

The formula given above for nepheline approximates to $R'AlSiO_4$. An artificial soda nepheline, $NaAlSiO_4$, and an artificial potash nepheline, $KAlSiO_4$, have both been made, and seem to correspond to the mineral, so that the formula $(K,Na)AlSiO_4$ may represent its true composition.

THE SODALITE GROUP

Another characteristic alkali-silicate of the elæolite-syenites is one which contains also chlorine, namely, the cubic substance **sodalite**, $Na_4(AlCl)Al_2(SiO_4)_3$, often found as a blue constituent of the rock, and the same mineral is found in druses of the ejected sanidine blocks of Mount Vesuvius in beautiful white dodecahedra accompanying meionite, augite, and leucite, or garnet and hornblende. The blue mineral named **haüyne**, found in rounded dodecahedra in druses of the ejected calcareous blocks of Vesuvius, seems to be isomorphous with sodalite; this mineral is remarkable as one of the few silicates which contain sulphur, and its formula, if expressed as $Na_2Ca(NaSO_4Al)Al_2(SiO_4)_3$, is analogous to that of sodalite.

Now **lapis-lazuli**, the beautiful blue substance found in Persia, and prized as an ornamental stone for ages, is also a soda-lime-alumina silicate containing sulphur and chlorine; it is natural to suppose that it bears a close relationship to the sodalite-haüyne group. For many years the ultramarine made from lapis has been replaced by an artificial colouring matter which is manufactured upon a large scale, and is prepared by the fusion of kaolin with sodium carbonate and sulphur. The chemical composition of the artificial ultramarine is not certain, but it is highly probable that its rich blue colour is due to the presence of the compound $Na_4(NaS_3Al)Al_2(SiO_4)_3$, which may conveniently be called lazurite.

Lapis-lazuli was formerly supposed to be a simple mineral, but Brögger and Bäckström have shown that it is really a rock consisting of diopside, amphibole, muscovite, calcite, and iron pyrites, together with a blue cubic mineral; this blue mineral has practically the composition just ascribed to lazurite, but is probably contaminated by isomorphous intermixture with haüyne and sodalite, which introduce a certain proportion of calcium and of chlorine. Lazurite is therefore to be

regarded as a cubic mineral belonging to the sodalite-haüyne group, and in this group the radicles (ClAl), ($NaSO_4Al$), (NaS_3Al) are supposed to be capable of mutual replacement.

True lapis-lazuli is a deep blue opaque substance variegated by bright specks of iron pyrites; the ancient quarries, which were visited by Marco Polo in 1271, are in Badakschan, above the valley of the River Kokcha, which flows into the Oxus; the precious mineral is found in a dark-coloured and a white limestone, and is extracted by heating the limestone with fires, and then breaking out the lapis-lazuli with hammers. It is probable that all the lapis of antiquity, for which various localities were given, really came from this spot. The mineral is called *sapphiros* by Pliny.

SECTION XX

THE FELSPAR GROUP

THE minerals of the felspar family derive their chief scientific interest from the fact that they are the most important of all rock constituents; indeed, the classification of most rocks depends to a large extent upon the particular felspar which they contain; the identification of felspars under the microscope is a matter of extreme moment to the geologist, and for this reason their optical properties have been the subject of much study. The rock-forming felspars occur for the most part only as small or microscopic crystals; but the potash felspar, orthoclase, occurs in large crystals, and in considerable masses, which are quarried for use in the manufacture of porcelain. This mineral, by its decomposition, also furnishes the china clay of commerce.

Feldspath is an old German or Swedish name of doubtful signification, which was in use as early as 1750. Several different varieties of the mineral were distinguished, first by their crystallographic, then by their chemical characters. The name orthoclase was used by Breithaupt (1823) to denote felspar with a rectangular cleavage (*i.e.* monoclinic felspar), and the name plagioclase was subsequently applied to the anorthic felspars whose cleavage angle is not 90°. He also introduced the name oligoclase for the soda felspar from Stockholm, which had been distinguished as a new mineral by Berzelius, and possessed an ill-defined cleavage. These names are universally employed at the present time. While, however, the potash felspar, orthoclase, became more firmly established as a definite species belonging to the monoclinic system, further study of the felspar containing soda and lime indicated that the composition of plagioclase is extremely variable, and led to the use of a great number of names to distinguish the varieties. Those most rich in lime were called anorthite, a name used by G. Rose (in 1823) for the glassy crystals found in the volcanic ejections of Vesuvius; those most rich in soda were called albite, a name originally used by Berzelius for a felspar from Fahlun in Sweden; many intermediate varieties were referred either to oligoclase, or to labradorite, a chatoyant mineral from Labrador. The various species were distinguished by their cleavage angles and blowpipe reactions, and by their specific gravity. An important character by which plagioclase could generally be distinguished

from orthoclase was the multiple twinning of the former. The plagioclase felspars usually consist of fine twin lamellæ parallel to B, whereas in orthoclase B is already a plane of symmetry, and therefore cannot be a twin plane. Consequently in plagioclase (Fig. 244) the C cleavage is traversed by fine bands due to the oscillatory combination of C_1, C_2 of Fig. 242; these planes are inclined to one another at 7° 12′ in albite, and at 8° 20′ in anorthite; they yield two reflecting surfaces, easily seen when C is viewed by reflected light. This is known as the "twin striation of plagioclase," and is clearly visible even on broken surfaces.

All felspars were naturally referred to one and the same family on account of the remarkable similarity of their cleavage, crystalline form, hardness, lustre, and specific gravity; but as their chemical nature became better understood they appeared to be widely different in composition. The potash felspar, orthoclase, and the soda felspar, albite, have a similar constitution, $R'AlSi_3O_8$, and yet belong to different systems, while the lime felspar, anorthite, has a totally different constitution, $R''Al_2Si_2O_8$, and yet appears to be completely isomorphous with albite. The different varieties of plagioclase contain all these elements, and are scarcely to be divided into distinct species.

In 1864 Tschermak propounded the theory of the felspar group which has now found universal acceptance. According to this theory the plagioclases are isomorphous mixtures of albite and anorthite, and can be represented as $m NaAlSi_3O_8 + n CaAl_2Si_2O_8$. The only pure soda felspar is albite ($SiO_2 = 68{\cdot}7$ %); the only pure lime felspar is anorthite ($SiO_2 = 43{\cdot}16$ %).

In the soda-lime felspars it was found that as the soda increases the silica increases and the alumina diminishes; but as the lime increases the silica diminishes and the alumina increases. These relations are in complete accordance with the above formula.

The names previously used rather indefinitely for the intermediate varieties can now receive greater precision of meaning as follows—using Ab to denote albite, and An for anorthite :—

Oligoclase = Ab to Ab_3An_1 ($SiO_2 = 68{\cdot}7$ to $61{\cdot}9$).
Andesine = Ab_3An_1 to Ab_1An_1 ($SiO_2 = 61{\cdot}9$ to $55{\cdot}4$).
Labradorite = Ab_1An_1 to Ab_1An_3 ($SiO_2 = 55{\cdot}4$ to $49{\cdot}1$).
Bytownite = Ab_1An_3 to An ($SiO_2 = 49{\cdot}1$ to $43{\cdot}16$).

Since most of the plagioclases also contain potash, we have to suppose either that monoclinic orthoclase can form isomorphous mixtures with anorthic plagioclase, or that potash felspar is dimorphous, and that a modification exists belonging to the anorthic system and capable of entering into these mixtures.

The latter view is supported by a discovery made in 1876 by Descloizeaux, who showed that many potash felspars are optically anorthic; he united these under the name microcline, which had been applied by Breithaupt to a chatoyant felspar from Fredriksvärn in Norway on account of its cleavage angle (89° 38′) differing but slightly from a right angle (*μικρός*, *κλίνω*). A beautiful green mineral, known as

"amazon-stone," from the Ilmen Mountains and other localities, was the most conspicuous example of these anorthic potash felspars. For later views on microcline see, however, p. 460.

ORTHOCLASE

Orthoclase.—$KAlSi_3O_8$; $K_2O = 16{\cdot}9$, $Al_2O_3 = 18{\cdot}5$, $SiO_2 = 64{\cdot}6$. Monoclinic.

$$a : b : c = 0{\cdot}658 : 1 : 0{\cdot}555. \quad \beta = 63^\circ\ 57'.$$

$m = \{110\}$, $C = \{001\}$, $B = \{010\}$, $x = \{101\}$, $y = \{201\}$, $n = \{021\}$, $o = \{\bar{1}11\}$.

$mB\ (110) : (010) = 59^\circ\ 24'$, $mm\ (110) : (1\bar{1}0) = 61^\circ\ 13'$, $Cx\ (001) : (101) = 50^\circ\ 17'$,

$Cy\ (001) : (201) = 80^\circ\ 18'$, $Cn\ (001) : (021) = 44^\circ\ 57'$.

Twinned on the prism edge [001] (Carlsbad law), or on (021) (Baveno law). Cleavage C, B, perfect; m, imperfect. Brittle. Fracture, conchoidal. H = 6; G = 2·5. Colourless. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1{\cdot}524$. Birefringence, negative, weak; $\gamma - \alpha = 0{\cdot}006$. Axial plane perpendicular to (010). Acute bisectrix inclined at 85° to the normal of (001) and 21° to the normal of (100). Extinction on $B = +5^\circ$; $2E = 120^\circ$. Fusible (5). Insoluble in acids.

With the above description compare crystals (adularia) from **St. Gothard.**

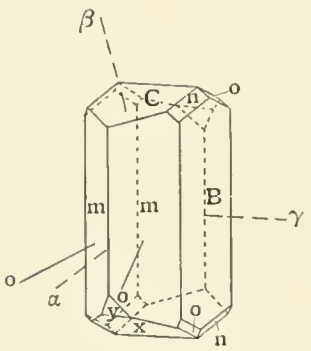

Fig. 589.—Orthoclase, B {010}, C {001}, m {110}, x {10$\bar{1}$}, y {201}, o {111}, n {021}.

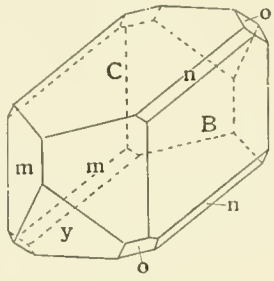

Fig. 590. — Orthoclase, B{010}, C{001}, m{110}, y{201}, o {1$\bar{1}$1}, n {021}.

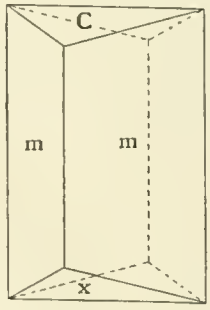

Fig. 591.—Orthoclase (Adularia), m {110}, C {001}, x {10$\bar{1}$}.

The usual crystals of **orthoclase**, which occur in druses in many granites, show the forms of Fig. 589. Typical examples are the white crystals of the Mourne Mountains, of the Colorado granite, and of the Cornish clay works. Three distinct habits may be recognised: (1) "Baveno habit" of Fig. 590, when the crystals are elongated along the edge BC, *e.g.* the pink felspar of the Baveno Granite Quarries; (2) "Sanidine habit," like Fig. 602, tabular along B, *e.g.* the large, dull gray felspar of the trachyte of the Drachenfels, to which this name was first applied (from σάνις, a table)—more perfect examples are the small, limpid, glassy crystals found in druses of the felspar blocks ejected from Mount Vesuvius; (3) "Adularia habit," Fig. 591, characteristic of the glassy crystals from St. Gothard, and called after the old name of that mountain or one of its spurs (Adula).

The cleavage faces C, B can always be recognised on orthoclase, and

the more perfect (C) is easily distinguished; owing to cleavage cracks the face C has a somewhat pearly lustre; the prismatic cleavage *m* is very imperfect, but is important, for it affords ready means of orientating a crystal of orthoclase. If the prism cleavages be placed vertical and the upper C cleavage sloping downwards and directed towards the observer, the crystal is placed in the normal position in which all the following diagrams are drawn. The face *x* is easily recognised as a plane almost symmetrical to C at the back of the crystal; this gives an apparently rhombic symmetry to the crystals of adularia, Fig. 591; *y*, on the contrary, is nearly at right angles to C; the prism *m* is often accompanied by smaller faces of *z* {130}.

The clino-pinakoid B is almost always vertically striated. The ortho-pinakoid A {100} is very rarely present.

In descriptions of felspar it has usually been customary to denote—

C {001} by P
B {010} by M
m {110} by T or *l*.

The twinning of orthoclase takes place on three laws which are named after typical localities in which specimens illustrating them were found.

(1) Carlsbad law: two individuals are united by the face B (Fig. 594) or partially interpenetrate (Figs. 592, 593), and are twinned by

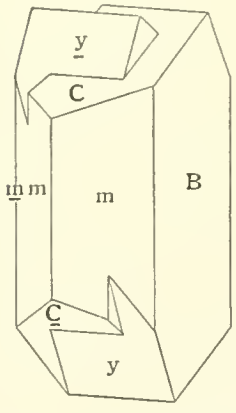

Fig. 592. — Orthoclase twinned on axis [001] (Carlsbad Law).

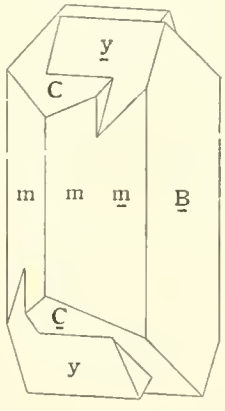

Fig. 593. — Orthoclase twinned on axis [001] (Carlsbad Law).

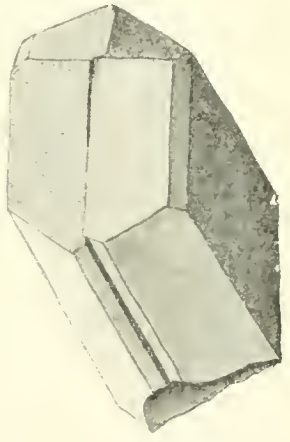

Fig. 594. — Orthoclase, top of a Carlsbad Twin, terminated by C, *x*, *n*.

hemitropy about the vertical axis or prism edge. Since C and *x* are nearly symmetrical, C of one crystal nearly falls into a plane with *x* of the other; they should really make an angle of 1° 50′ with each other (Fig. 594), and even if this angle cannot be detected by the eye, it is easy to see that, of the two faces which appear to fall into a plane, one is a cleavage face while the other is not. The crystals may be united either as in Fig. 592 or Fig. 593, and these are sometimes distinguished as right-handed and left-handed Carlsbad twins. Fig. 594 shows not

only that C_1, x_2 are not quite in a plane, but also that x is dull while C is smooth and bright.

(2) Baveno law: two individuals (generally of the Baveno habit) are twinned about n (021) and are united by that plane. Since the angles Cn and Bn are very nearly 45°, the crystal remains an almost

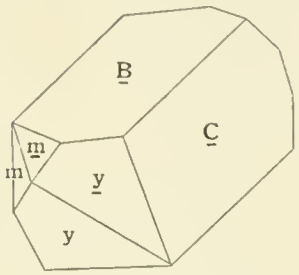

Fig. 595.—Orthoclase twinned on (021) (Baveno Law).

Fig. 596.—Orthoclase, Baveno Twin, on Quartz.

rectangular prism and may at first sight be mistaken for a single individual, but examination of the cleavage will show that two C faces are adjacent at one edge, and two B faces at the opposite edge. The two ends of the crystal show a characteristic diagonal line of union; at one end faces m and y meet at small salient angles across this line, as shown in Fig. 595: $mm = 10° 34'$, $yy = 13° 42'$; at the other end are corresponding re-entrant angles. Fig. 596 represents a characteristic Baveno twin attached to a crystal of quartz.

Repetition on this law with inclined twin planes may give rise to a quartet, as in Fig. 597, in which the rectangular prism is now bounded by

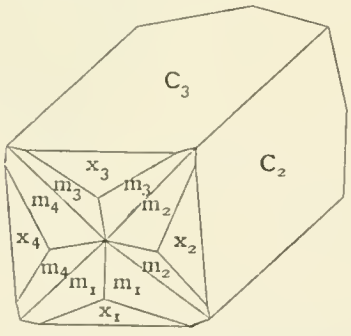

Fig. 597.—Orthoclase, Quartet, twinned on {021}.

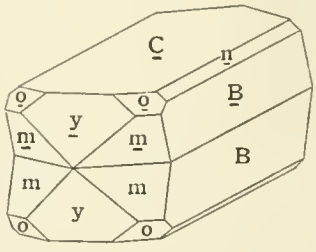

Fig. 598.—Orthoclase twinned on (001) (Manebach Law).

four faces, C, corresponding to the more perfect cleavage; the re-entrant angles give a stellate appearance to the end of the crystal; a fifth crystal twinned upon No. 4 would almost coincide with No. 1. It is clear from Fig. 595 that a quartet may equally well be bounded by four B faces.

(3) Manebach law: two individuals twinned upon C (001) are united along that plane, Fig. 598. Here the faces B, B of the two individuals fall into a single plane.

The Baveno and Manebach laws are sometimes combined in a single twin group; it is then often difficult to say which law is operating. Thus in Fig. 597 the individuals 1 and 3 are in almost exactly the same relative positions as the two individuals of Fig. 598; in Fig. 598 the faces C, C are parallel; in Fig. 597 the faces C_1, C_3 are inclined at 14′ (since $cn = 45^\circ\ 3\frac{1}{2}'$ and, therefore, $C_1C_2 = 90^\circ\ 7' = C_2C_3$). It would, therefore, require very accurate measurements to say whether Fig. 597 is a Baveno quartet, or an interpenetration of two Manebach twins (C_1C_3 and C_2C_4) twinned together on the Baveno law.

The optical characters of orthoclase seem to be somewhat variable; the negative acute bisectrix always emerges at about 5° to the crystal axis *a*, and the extinction with regard to the edge BC is, therefore, + 5° on B, and 0° on C. In adularia the positive obtuse bisectrix is normal to B and the true angle of the optic axes is about 70°, so that they are only slightly inclined to the normals of the prism {110}; but in some specimens the angle 2V is as great as 85°, while in others it is so small that the crystal is nearly uniaxial.

Descloizeaux found that change of temperature produced a remarkable effect upon the position of the optic axes. For example, a sanidine crystal, for which at 18° C. the value of 2E was 13°, became uniaxial for red light at 42° C.; at a higher temperature the optic axes separated out in the vertical plane, so that the plane of the optic axes became parallel to B (010) instead of perpendicular to B, as it was at 18° C.; on cooling, these changes are reversed and the axes regain their original directions; unless the crystal has been heated above 600° C., when the change becomes permanent.

Now the various stages of this change are also exemplified by crystals as found in nature. Some orthoclase (1) has the normal characters of Fig. 589, with the axial plane nearly parallel to C; some (2) is nearly uniaxial; some (3) has the axial plane parallel to B: there is generally a well-marked dispersion; this must be horizontal in Class (1) and inclined in Class (2) (*cf.* p. 158). Most orthoclase possesses the optical characters given in Fig. 589; a possible cause of the variations is the pseudo-symmetric structure mentioned on p. 460.

Some orthoclase possesses a pearly opalescence (*e.g.* the Ceylon "moonstone"), and this usually accompanies a parting parallel to the ortho-pinakoid {100}, or to an ortho-dome near {801}, and appears to be due to lamination of different felspathic material, or to inclusions, or to decomposition parallel to that face; it is most conspicuous when (100) is turned towards the observer, and is generally of a pale blue colour.

The colour of orthoclase varies widely, from the colourless glassy sanidine and adularia to the ordinary white, gray, yellow, or flesh-coloured crystals of common granite; most orthoclase is turbid or opaque, owing to partial conversion into kaolin.

Orthoclase often contains a considerable proportion of sodium, which

is probably in most cases due to an intermixture of albite (see, however, anorthoclase, p. 461); these varieties are much more fusible than ordinary orthoclase, which melts at about 1150° C.

Some Noteworthy Localities:

Mount Vesuvius.—The ejected blocks of Monte Somma often consist of a pure white granular orthoclase, together with plagioclase, nepheline, and sodalite; in the cavities of this rock are beautiful little glassy plates of sanidine with the usual faces B, *m*, C, *x*, *y*, *o*, *n* (Fig. 589); the lustre of the B faces sometimes indicates lamellar Carlsbad twinning.

Rhenish Prussia.—The trachyte (sanidinite) of the **Laacher See** contains in its cavities large white crystals of the usual tabular habit;

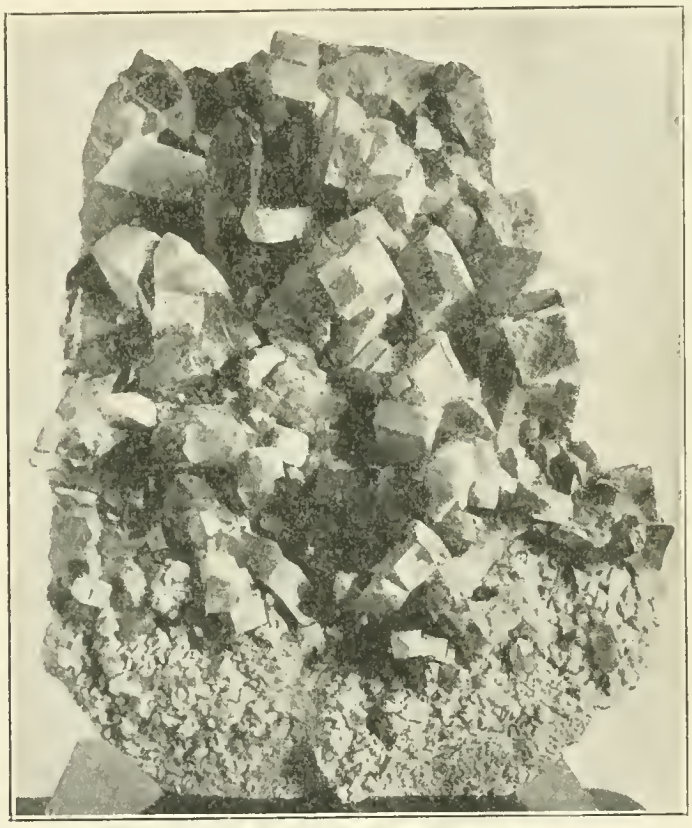

Fig. 599.—Orthoclase on Granite, from Baveno (British Museum).

sometimes these are red, owing to alteration and staining with iron; they are remarkable for the entire absence of twinning. The masses which contain these crystals seem to be also volcanic ejected blocks. Among the associated minerals are to be noticed nosean, nepheline, biotite, olivine, augite, hornblende.

The neighbouring trachyte of the **Drachenfels** contains large gray porphyritic crystals of tabular sanidine, which are usually Carlsbad twins; they have characteristic vertical streaks on B, due to microscopic cavities. The simple crystals are square prisms (B, C). The crystals are here often broken and the fragments found not far removed from each other, showing that they were formed prior to the consolidation of the rock.

Baveno.—The Baveno quarries in Piedmont furnish fine, flesh-coloured, opaque crystals lining cavities in the red granite with quartz and mica; the crystals are of the Baveno habit, and mostly Baveno twins, triplets, etc., but Carlsbad twins are by no means rare. Fig. 599 is a photograph of a specimen in the British Museum.

St. Agnes (Cornwall).—At many localities in Cornwall the granite contains large porphyritic crystals of orthoclase; Carlsbad twins are very frequent, and the crystals are often wholly or partly converted into white kaolin, so that they are usually opaque, and rough in outline. At **Huel Coates** (St Agnes) pairs of Carlsbad twins sometimes interpenetrate and cross one another at angles which point to twinning upon other laws, *e.g.* (111) and (051) as twin planes. At this locality the crystals are sometimes completely converted into a brownish granular aggregate of cassiterite and quartz.

Mourne Mountains (County Down).—Druses of the gray granite are lined with sharp, white, opaque orthoclase of Baveno habit, showing the forms B, C, *m*, *x*, *y*; Carlsbad, Baveno, and also Manebach twins occur. With these are associated smoky quartz and zinnwaldite, and sometimes also topaz and beryl. The white orthoclase has sometimes a peculiar pearly lustre.

St. Gothard.—The granite and gneiss of this district furnish abundant orthoclase, associated with quartz, chlorite, mica, apatite, albite, and hæmatite; especially characteristic are glassy crystals of the Baveno habit, and Baveno twins, in which the faces B are covered and partly permeated with fine chlorite, while C is bright and smooth, with the usual pearly lustre. These crystals are often deeply corroded. The adularia of this and the other Swiss localities is often quite opaque and green with enclosed chlorite. When the faces C, *m* are of nearly the same size the adularia crystals resemble rhombohedra; but C may always be recognised as a cleavage face; it is striated horizontally.

OTHER FELSPARS ALLIED TO ORTHOCLASE

Microcline is the name given to anorthic potash-felspar. In chemical composition, hardness, specific gravity, and general characters microcline is indistinguishable from orthoclase; a felspar is only referred to microcline when its cleavage angle, twinning, or optical properties point to the anorthic system. Chief among these characters is the twin lamellation parallel to B, which gives the characteristic plagioclase striæ on the face C; these render the cleavage angle difficult to determine, since simple untwinned crystals of microcline are almost unknown; BC has been measured as 89° 25′ to 89° 45′, generally about 89° 30′.

The optical characters are still more difficult to determine, owing to the fact that the twinning takes place both according to the albite law (twin plane, B) and the pericline law (twin axis, the edge C*x*); this divides the crystal into a number of intersecting twin lamellæ at right angles to each other, and produces a curious rectangular grating-structure or cross-hatching, visible between crossed nicols, and known as the micro-

cline structure (Fig. 600); in sections parallel to the basal plane this generally presents the appearance of two series of tapering lamellæ. So far as they can be ascertained, the optical characters resemble those of orthoclase, except that the extinction on C is not straight but + 15° 30′, and the obtuse positive bisectrix is not perpendicular to B but inclined at 15° 26′ to its normal. The axial angle is also larger than in orthoclase, $2H = 89°$ about; as viewed along the obtuse bisectrix (through the B cleavage) the dispersion is $\rho < v$.

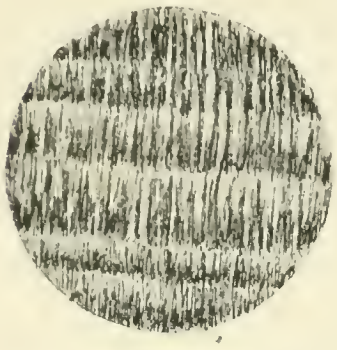

Fig. 600. Section of Microcline between crossed nicols.

The name "amazon-stone" is given to the green varieties.

Some Noteworthy Localities:

Pike's Peak (Colorado).— In the albitic granite of the Pike's Peak region beautiful large crystals of amazon-stone occur (Fig. 601); these are of the usual orthoclase habit, and sometimes twinned on the Baveno, Manebach, and Carlsbad laws.

The albitic granite of the **Ilmen Mountains** in Russia has furnished precisely similar light green crystals, and in both localities among the

Fig. 601.—Microcline (Amazon-stone) from Pike's Peak.

accompanying minerals are smoky quartz, topaz, and glassy rhombohedral crystals of the rare beryllium silicate, phenacite.

Doubts have been entertained regarding the monoclinic symmetry of orthoclase, on account of irregularities in angles and cleavages. Now it appears highly probable that if the cross twinning and interpenetration of microcline became so minute as to be invisible under the microscope the crystals would be indistinguishable from those of orthoclase,

and would, in fact, possess all the properties of that mineral. Many authors regard orthoclase and microcline as one and the same mineral, and describe orthoclase as pseudo-symmetric; if this be so, all the felspars may be in reality anorthic.

Anorthoclase (*Germ.* Natronmikroklin) is a soda-potash felspar, $(Na,K)AlSi_3O_8$, which resembles microcline in having a cleavage angle not quite 90°, and in possessing the cross-hatched structure due to multiple twinning on two laws, but this is sometimes so fine as to be scarcely visible. It is the felspar characteristic of certain groups of alkaline rocks, *e.g.* the lavas of the Island of Pantelleria. In some localities the crystals assume quite a peculiar habit, owing to the predominance of *y* and to elongation along the vertical axis; the "rhomben-porphyr" of Christiania receives its name from the rhombic outlines of the porphyritic crystals of this felspar which it contains (forms C, *y*, *m*). Anorthoclase always contains also a little lime.

Hyalophane, remarkable as a barium felspar, is a monoclinic mineral found in little glassy crystals of adularia habit (*mx*C), like Fig. 591, in the white dolomite of the Binnenthal, which has already been mentioned as a locality for blende and other minerals. The crystals occur in cavities of the dolomite associated with barytes, realgar, pyrites, and other metallic sulphides and sulpharsenides.

Hyalophane corresponds to the formula $K_2BaAl_4Si_8O_{24}$ (not isomorphous (K_2, Ba)), and this can be expressed as a mixture of $BaAl_2Si_2O_8$ with $2KAlSi_3O_8$, *i.e.* as compounded of two molecules of orthoclase with one molecule of a barium silicate similar to anorthite.

This union is exactly analogous to the mixture of albite and anorthite in the group which we have next to consider, the plagioclase group; but in hyalophane the mixture appears to be only in one definite proportion, so that the mineral is to be regarded as a double salt rather than a solid solution.

THE PLAGIOCLASES

Albite, Anorthite, and their Mixtures

Albite.—$NaAlSi_3O_8$; $Na_2O = 11{\cdot}8$, $Al_2O_3 = 19{\cdot}5$, $SiO_2 = 68{\cdot}7$. Anorthic; symmetry, holosymmetric.

$$a : b : c = 0{\cdot}6335 : 1 : 0{\cdot}5577. \quad \alpha = 94^\circ\ 3', \beta = 116^\circ\ 29', \gamma = 88^\circ\ 9'.$$

$$B = \{010\}, C = \{001\}, m = \{110\}, M = \{1\bar{1}0\},$$

$$x = \{10\bar{1}\}, y = \{201\}, o = \{111\}.$$

$$BC\ (010) : (001) = 86^\circ\ 24', Bm\ (010) : (110) = 60^\circ\ 26',$$

$$mM\ (110) : (1\bar{1}0) = 59^\circ\ 14'.$$

$$Cm\ (001) : (110) = 65^\circ\ 17', CM\ (001) : (1\bar{1}0) = 69^\circ\ 10', Bo\ (010) : (111) = 66^\circ\ 18',$$

$$Cx\ (001) : (10\bar{1}) = 52^\circ\ 16', Cy\ (001) : (20\bar{1}) = 82^\circ\ 7'.$$

Common twins; on plane B (010) (albite law); on an edge C*x* [010] (pericline law). Cleavage C, perfect; B, *m*, imperfect. Brittle. Fracture, uneven. H = 6; G = 2·63. Colourless. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1{\cdot}533$. Birefringence, positive, weak; $\gamma - \alpha = 0{\cdot}011$. Acute bisectrix in the zone BC inclined at 15° 36′ to the normal of B, and at

102° to the normal of C. Obtuse bisectrix inclined at 70° to the normal of C; $2H = 82°$. $\rho < v$. Fusible (4). Insoluble in acids.

With the above description compare crystals from **Schmirn** (Tyrol).

Albite, as is signified by the name, usually occurs in white crystals, and the best are found lining cavities in granite or in gneiss and the crystalline schists. Albitic granite is the source of many rare and interesting minerals, and the presence of albite is often an indication that such minerals may be found; *e.g.* the topaz and beryl of the Mourne Mountains; the phenacite and topaz of Pike's Peak and the Ilmen Mountains; the topaz, tourmaline, etc., of the Urals.

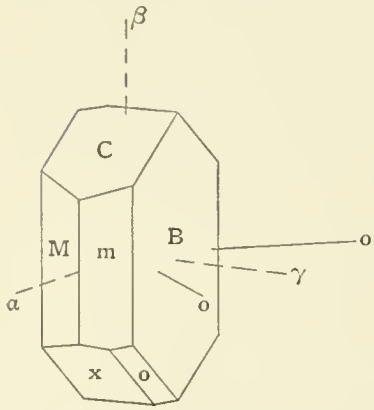

Fig. 602.—Albite, B {010}, C {001}, *m* {110}, M {1$\bar{1}$0}, *x* {10$\bar{1}$}, *o* {1$\bar{1}$1}.

Ordinary albite is, like Fig. 602, tabular along B; when B is small and the crystals are elongated along the edge C*x* (the axis *b*) the crystals are usually called "pericline"; this name ($\pi\epsilon\rho\iota\kappa\lambda\iota\nu\acute{\eta}\varsigma$ = sloping) was given in allusion to the oblique aspect of the crystals (Figs. 604, 605). As in orthoclase, the face B is vertically striated. Twinning on B (Fig. 603) is so common that this, the characteristic twin law of plagioclase, is known as the albite law; the faces C, easily recognised by their pearly lustre, make an angle (generally re-entrant, at the exposed end of the

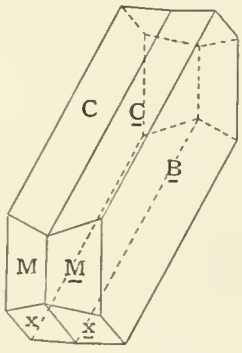

Fig. 603.—Albite twinned on (010) (Albite Law).

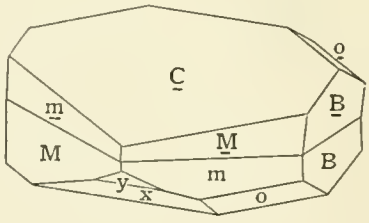

Fig. 604.—Albite twinned on the axis [010] (Pericline Law).

crystal) of 7° 12′. Few specimens of albite fail to show this twinning, and it is often repeated as a lamellation.

Pericline is usually twinned according to a different, the so-called "pericline law"; two individuals having contact somewhat nearly along the plane C are derived from each other, not by reflection over this plane, but by a semi-rotation about the edge C*x* [010]. Fig. 604 shows that the faces B, B in such a twin do not fall into a plane, and that their line of intersection is not parallel to the edge CB, but makes an appreciable angle (27° 14′) with it (see below, p. 465). Twinning on

the Carlsbad, Baveno, and Manebach laws also occurs in albite, but far more rarely than in orthoclase.

In fusibility, refractive index, and hardness, albite somewhat closely resembles orthoclase, but is readily distinguished from it by its higher specific gravity, as shown by means of a heavy liquid.

In composition albite is entirely analogous to orthoclase, and the two minerals exhibit very close relationships; parallel growths of albite on orthoclase and of orthoclase on albite occur at several localities (see Fig. 383, p. 238); in these the prism zones coincide, and the faces B, *m*, M are approximately parallel to each other. Still more intimate associations occur; at Perth in Ontario a red felspar was found, which was described in 1843 as a soda orthoclase, under the name "perthite." This was subsequently shown to be a parallel intergrowth, in which the laminæ of albite are parallel to the ortho-pinakoid {100} of the orthoclase; many other such intergrowths are now known, and the finer varieties are distinguished as microperthite or cryptoperthite, and then finally pass into anorthoclase.

From Canada also (Bathurst County) comes "peristerite," an opalescent white albite corresponding to the moonstone of Ceylon; it possesses the same bluish sheen when viewed towards the ortho-pinakoid; the name is given in allusion to the colour, from περιστερά, a dove.

Some Noteworthy Localities:

Mount Scopi (Switzerland).—A white micaceous gneiss has its cavities copiously lined with crystals of pericline. These are usually covered with, or partly permeated by chlorite, and accompanied by titanite, adularia, axinite, and apatite, and are the usual pericline twins. The twin groups are sometimes triplets or quartets united on the pericline law, and may also contain laminæ parallel to B twinned on the albite law. Here and in the Maderanerthal small crystals of adularia are sometimes situated in parallel position on the pericline.

Fig. 605.—Albite (Pericline) from Zermatt.

Very similar specimens are found in the gneiss and mica-schist of the **St. Gothard** district, in Canton Wallis (Fig. 605), and at **Zillerthal**, **Pfitsch**, and other localities in the Tyrol. Some of the best colourless albite crystals have been found with calcite lining druses in the limestone of **Schmirn** (Tyrol).

Tintagel (Cornwall).—The cracks of a silky slate are lined with albite and quartz together with calcite; the albite (B, C, *m*, M, *o*, *n*, *x*, *y*, etc.) almost always twinned on B; fine hairlike crystals of rutile (sagenite) also occur on the specimens.

Anorthite.—$CaAl_2Si_2O_8$; $CaO = 20{\cdot}12$, $Al_2O_3 = 36{\cdot}72$, $SiO_2 = 43{\cdot}16$. Anorthic; symmetry, holosymmetric.

$a : b : c = 0{\cdot}6347 : 1 : 0{\cdot}5501$. $\alpha = 93^\circ\ 13'$, $\beta = 115^\circ\ 55'$, $\gamma = 91^\circ\ 12'$.

B = {010}, C = {001}, A = {100}, m = {110}, M = {1$\bar{1}$0},
x = {10$\bar{1}$}, y = {201}, o = {111}, v = {2$\bar{4}$1}, f = {130}, n = {021}, e = {0$\bar{2}$1},
k = {023}, a = {11$\bar{1}$}, m' = {1$\bar{1}$1}, t = {20$\bar{7}$}.

BC (010) : (001) = 85° 50′, Bm (010) : (110) = 58° 4′, mM (110) : (1$\bar{1}$0) = 59 29′,
Cm (001) : (110) = 65° 53′, CM (001) : (1$\bar{1}$0) = 69° 20′, CA (001) : (100) = 63° 57′,
Cx (00$\bar{1}$) : (10$\bar{1}$) = 51° 26′, Cy (001) : (201) = 81° 14′, Ce (001) : (0$\bar{2}$1) = 42° 38′.

Twinned on edge [001] (Carlsbad law), on face (010) (albite law), on face (021) (Baveno law), on face (001) (Manebach law). Cleavage C, perfect; B, less perfect. Brittle. Fracture, conchoidal. H = 6½; G = 2·75. Colourless. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1{\cdot}58$. Birefringence, weak, negative; $\gamma - \alpha = 0{\cdot}013$. Obtuse bisectrix perpendicular to e. Acute bisectrix inclined inside the crystal at 53° 14′ to normal of C (001), at 58° to normal of B (010), at 16° 52′ to normal of o (11$\bar{1}$); 2H = 85°; $\rho < v$. Fusible (5). Decomposed by hydrochloric acid with gelatinisation.

With the above description compare crystals from **Vesuvius**.

Pure **anorthite** is a rare mineral; the beautiful glassy crystals from Vesuvius contain very small proportions of soda and potash, and the crystallographic and optical data are derived from their study. Fig. 606 illustrates the rich combination of forms on these crystals, in which also twinning has been observed according to the albite, pericline, Carlsbad and Manebach laws. The habit of the crystals is very varied. The B faces are not so markedly striated as in orthoclase and albite. The less ready fusibility and the more ready action of acids distinguish anorthite from these minerals. As explained on p. 236 and below, observation in parallel and convergent light of cleavage flakes parallel to C and B serves to distinguish these three principal felspars from each other.

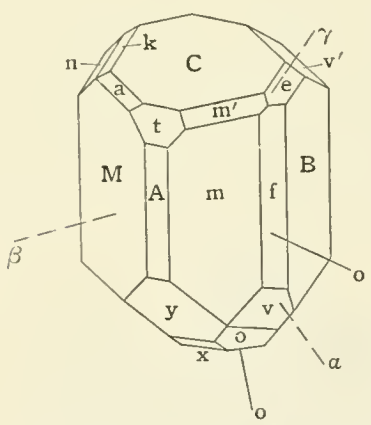

Fig. 606.—Anorthite, A {100}, B {010}, C {001}, m {110}, M {1$\bar{1}$0}, f {130}, t {20$\bar{7}$}, m' {1$\bar{1}$1}, e {0$\bar{2}$1}, k {0$\bar{2}$3}, n {021}, y {201}, x {10$\bar{1}$}, o {111}, v {2$\bar{4}$1}, v' {$\bar{2}$41}, a {11$\bar{1}$}, from Vesuvius.

Some Noteworthy Localities:

Mount Vesuvius.—Limpid glassy crystals occur in cavities of the ejected blocks of Monte Somma (Fig. 606); in the limestone blocks they are accompanied by mica, in the augitic blocks by leucite (glassy), spinel (dark octahedra), meionite (glassy square prisms).

Japan.—In the basalt of **Miyake Island**, large, white, opaque, porphyritic crystals, covered with a black crust; forms C, B, y, m, M; frequently Carlsbad twins.

The Intermediate Plagioclases—Oligoclase to Bytownite :

The various soda-lime felspars are, for the most part, less perfectly crystallised than albite and anorthite, and many of them are chiefly known as rock constituents, either massive, porphyritic, or microscopic, but usually without well-defined faces. Now that the law of their composition as isomorphous mixtures of albite and anorthite is established, the composition of any specimen and its place in the series may be determined by the specific gravity and the optical examination of cleavage flakes C and B, as described on pp. 234-6. The following table summarises the essential data for albite and anorthite—the two ends of the series—and for five of the intermediate mixtures whose compositions are given in the second column. The numbers in any column being plotted out as a curve according to the composition, the value for any other intermediate plagioclase of known composition may be found from its place on the curve.

For practical purposes the extinction angles on C and B are most convenient, and are sufficient, but the twinning sometimes renders their determination difficult.

		Sp. Gr.	SiO_2.	Extinction on C.	Extinction on B.	β.	Visible through B; Angle with Normal.	Angle of Rhombic Section.
Orthoclase .		2·565	64·6	0° 0′	+5°	1·523	+ Bis. 0° 0′	
Microcline .		2·56	64·6	+15° 30′	+5°	1·526	+ Bis. 15° 20′	
Albite . .	Ab	2·624	68·7	+ 4° 30′	+19°	1·534	+ Bis. 15° 36′	+27°
Oligoclase-albite	Ab_6An	2·645	64·9	+ 2° 45′	+12°			+10°
Oligoclase .	Ab_3An	2·659	62·0	+ 1° 4′	+ 4° 36′	1·542		+ 3°
Andesine . .	AbAn	2·694	55·6	− 5° 10′	−16°	1·558		− 1°
Labradorite .	$AbAn_3$	2·728	49·3	−17° 40′	−29° 28′	1·570		− 9°
Bytownite .	$AbAn_6$	2·742	46·6	−27° 33′	−33° 29′			−10°
Anorthite .	An	2·758	43·2	−37°	−36°	1·582	opt. Ax. 43° 12′	−16°

For quartz, specific gravity = 2·653 ; $\omega = 1·544$; $\epsilon = 1·553$.

The last column gives the angle between the edge CB and the line of union on the face B between the individuals of a pericline twin.

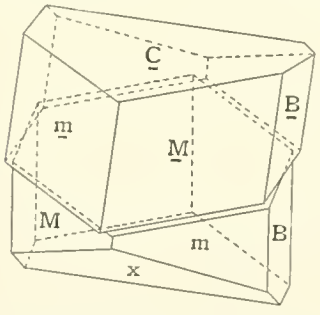

Fig. 607.—Plagioclase twinned on axis [010] (Pericline Law).

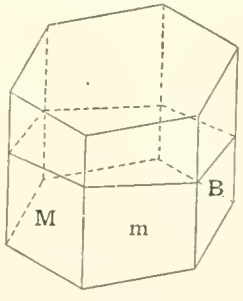

Fig. 608.—Albite, Rhombic Section.

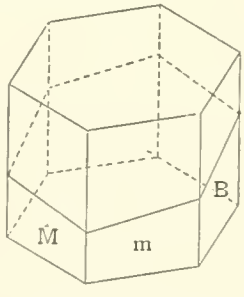

Fig. 609.—Anorthite, Rhombic Section.

It can be shown that if the two albite crystals of Fig. 607 meet uniformly, as in Fig. 604, their plane of contact is not parallel to

C, but is a plane whose intersection with the prism faces M, *m* is a rhomb; for this reason it is called the rhombic section; its inclination to the basal plane depends upon the angles of the crystal. Fig. 608 shows the position of the rhombic section for albite, Fig. 609 for anorthite. The trace of this plane on B makes an angle of + 27° with the edge BC in albite, and − 16° in anorthite (the terms + and − being used in the same sense as for the extinctions on B (cf. Fig. 381). For the intermediate plagioclases the angle has intermediate values.

The directions of the bisectrices and optic axes can be understood from

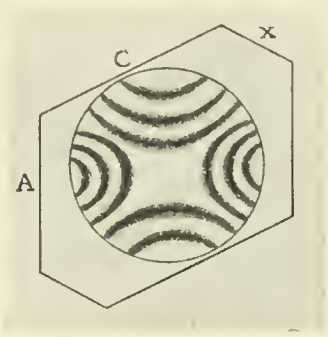

Fig. 610.—Albite, Cleavage B (010).

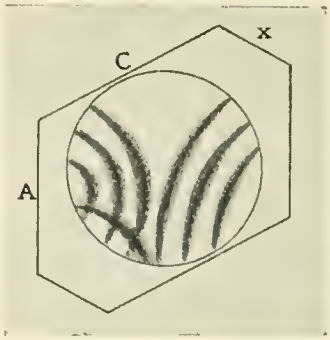

Fig. 611.—Labradorite, Cleavage B (010).

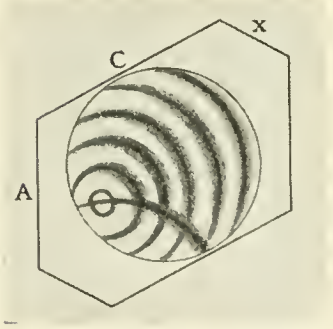

Fig. 612.—Anorthite, Cleavage B (010).

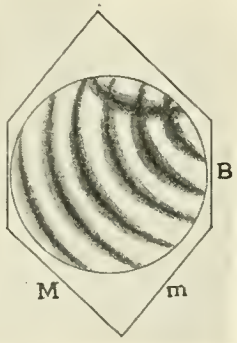

Fig. 613.—Labradorite, Cleavage C (001).

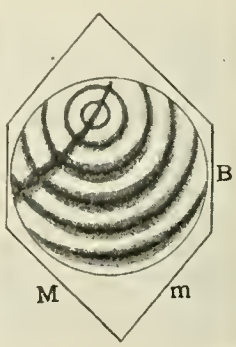

Fig. 614.—Anorthite, Cleavage C (001).

Fig. 382 (p. 235); as we pass down the series from albite to anorthite the positive bisectrix travels from γ_{Ab} to γ_{An}, and the negative bisectrix from α_{Ab} to α_{An}; the angle 2V is about 77° for all. The interference figures yielded in convergent light by cleavage flakes B for albite, and B and C for labradorite and anorthite, are shown in Figs. 610 to 614.

The mean refractive index (column 7, p. 465) may be approximately determined by the total reflectometer or by immersion in liquids of known refractive index, or sometimes in rock sections (when the felspar is in contact with a crystal of quartz), by Becke's method, described on p. 260. The refractive indices of quartz lie between those of oligoclase and andesine; it is therefore not difficult to say whether the felspar belongs to the more acid plagioclases above oligoclase in the table on p. 465, or the more basic plagioclases below andesine in the series.

The comparative readiness with which they yield to acids also dis-

tinguishes the basic from the acid plagioclases; on the other hand, the latter are the more fusible.

Chemical tests are not often used to distinguish the various members of the series, for in general they all contain not only soda and lime but also potash. Careful comparative tests of the flame colour imparted to a Bunsen burner (Szabo's flame test) yield a sufficiently reliable estimate of the relative proportions of soda and lime to place a plagioclase approximately in its position in the series; a qualitative examination for calcium is also useful as a confirmatory test. The presence of potash in small quantities in most plagioclases suggests that they may also contain an isomorphous admixture of microcline, anorthoclase, or orthoclase. Zonal growths of one felspar with another or with several others are very common in rocks; sometimes in section these may be discerned as regular bands surrounding a nucleus, the extinctions in successive bands being different. Where the composition gradually changes from the nucleus to the exterior, the crystal, as a whole, does not possess a definite extinction, but a wave of shadow passes over it inwards or outwards as the section is rotated between crossed nicols.

The following are typical examples of a few of the most conspicuous plagioclases :—

Oligoclase.—At **Arendal** in Norway, veins in the granite contain large yellowish crystals of oligoclase with orthoclase, quartz, epidote, garnet, and calcite. They are generally of pericline habit and pericline twins, but sometimes present much the appearance of orthoclase; the positive inclination of the rhombic section shows that they belong to the albite end of the series. The mineral has approximately the composition Ab_4An_1 to Ab_6An_1.

At Tvedestrand, not far from Arendal, in gneiss, are found reddish cleavable masses of the mineral known as "sunstone." This is a beautiful "avanturine" (or spangled) felspar with a golden shimmer or sparkle which appears to be due to enclosed scales of hæmatite or göthite. The plagioclase striation on C can usually be seen, and the small inclination of the rhombic section can sometimes be made out. The mineral has nearly the composition Ab_3An_1.

Andesine.—At **Bodenmais** in Bavaria the remarkable rock of the Silberberg consists in part of a dark green, somewhat greasy, felspar associated with magnetite, biotite, pyrrhotite, chalcopyrite, quartz, etc. This felspar is partly orthoclase, but partly a mineral exhibiting the plagioclase striation, and sometimes a microcline structure. The specific gravity, 2·68, and composition ($SiO_2 = 58\%$), of such specimens justifies their reference to andesine, but the mineral is so mixed with orthoclase, and other felspar, that the determination is difficult.

It will be seen on referring to the table on p. 465 that some varieties of andesine or oligoclase-andesine may be easily mistaken for orthoclase, for the extinction on C and B may be about 0° and + 5° respectively, and the rhombic section may appear to be parallel to C. In such a felspar, however, the specific gravity will be higher than that of orthoclase, and nearly equal to that of quartz.

Labradorite.—On the coast of **Labrador** occur masses of a rock consisting mainly of hypersthene and labradorite. Both minerals may be beautifully iridescent, and the specimens, much used for decorative purposes, are known as "labrador spar." The labradorite is found in quite large masses and shows a magnificent play of colours, generally blue, but also green, yellow, or red; the twin lamellæ being often very conspicuous as bands of different colour, generally indicative of the albite law. The iridescence is an interference effect due mainly to fine lamellar inclusions, which may be diallage, hæmatite, ilmenite, or göthite. It is difficult to determine the characters of the felspar with certainty, but the specific gravity (up to 2·7), the extinction angles ($+5^\circ$ and -17°), and the composition ($SiO_2 = 54$ to 56%) indicate that the mineral possesses nearly the constitution Ab_1An_1, and belongs to the andesine end of the labradorite section.

Bytownite.—Well-defined crystals of the most basic plagioclases are rare; they mostly occur as constituents of basalts, gabbros, serpentinous and other basic rocks. The name was given to the felspar of a rock from **Bytown** in Canada, which ultimately proved to be a mixture of anorthite with other felspars. The high extinction angles are sufficient to identify the more basic plagioclases in rock sections, and to distinguish them from the more acid. The usual method is to examine a large number of the crystal sections and determine the *maximum* extinction in the zone BC; this for a bytownite will amount to 37°, whereas for an oligoclase it will not rise above 2°. The rock-forming felspars are generally elongated along the zone BC.

SECTION XXI

SILICATES CONTAINING HALOGENS

THE MICA GROUP

Mica (*Germ.* Glimmer).—The micas are of very common occurrence as constituents of granites, gneisses, and schists, and some varieties are largely worked for commercial purposes, for use as lamp chimneys, electrical insulators, etc. They crystallise in forms which are nearly hexagonal, and possess a highly perfect basal cleavage. Before the days of chemical analysis they were distinguished from talc, gypsum, and other such cleavable minerals by the fact that cleavage flakes are highly elastic and not pliable.

In reality a large number of different, though, no doubt, closely related minerals, are included under the name mica. They are all silicates of aluminium and of either K, Na, Li (the alkali micas), or of Fe, Mg (the ferro-magnesian micas), generally containing also F, and water of constitution (H or OH ?).

The best defined crystals are those of the ferro-magnesian mica, biotite, which are found as glistening green, black, or reddish crystals in the ejected blocks of Monte Somma (Mount Vesuvius), together with other well-crystallised minerals. These we may take as a type of the micas, and to them the following description applies.

Biotite. — Silicate of aluminium, magnesium, iron and potassium. A typical analysis gave $SiO_2 = 39{\cdot}30$, $Al_2O_3 = 16{\cdot}95$, $Fe_2O_3 = 7{\cdot}86$, $MgO = 21{\cdot}89$, $K_2O = 7{\cdot}64$, $H_2O = 4{\cdot}02$, $F = 0{\cdot}89$, together with a little FeO, MnO, CaO and Na_2O, corresponding (only approximately) to $K_2HMg_6Al_3(SiO_4)_6$. Monoclinic.

$$a : b : c = 0{\cdot}577 : 1 : 3{\cdot}274. \quad \beta = 90^\circ\ 0'.$$

$$M = \{221\},\ B = \{010\},\ C = \{001\},\ \mu = \{11\bar{1}\}.$$

$$\mu\mu\ (11\bar{1}) : (1\bar{1}1) = 59^\circ\ 14',\ C\mu\ (001) : (\bar{1}11) = 81^\circ\ 19',\ MM\ (221) : (2\bar{2}1) = 59^\circ\ 48',$$

$$CM\ (001) : (221) = 85^\circ\ 38';\ 110 : 1\bar{1}0 = 60^\circ\ 0'.$$

Twins ; twin plane parallel to (110) ; face of combination C. Cleavage C, perfect. Laminæ elastic. Fracture, uneven. $H = 2\frac{1}{2}$; $G = 2{\cdot}86$. Acute bisectrix inclined at $0^\circ\ 30'$ to normal of C. Plane of optic axes parallel to B ; $\beta = 1{\cdot}6$. Birefringence, negative, strong ; $\gamma - \alpha = 0{\cdot}04$; $\rho < v$; $2E = 12^\circ\ 48'$ for yellow,

12° 22′ for red. Pleochroic, a green, β and γ dark brown. Translucent. Colour, dark green. Lustre, vitreous. Streak, colourless. Fusible with difficulty. Decomposed by sulphuric acid, leaving a skeleton of silica.

With the above description compare crystals from **Vesuvius.**

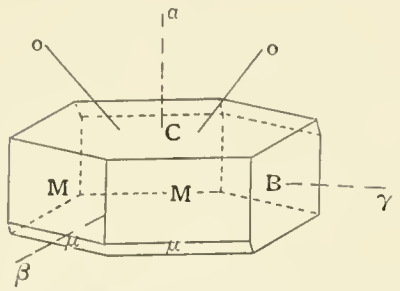

Fig. 615.—Muscovite, C {001}, B {010}, M {221}, μ {11$\bar{1}$}.

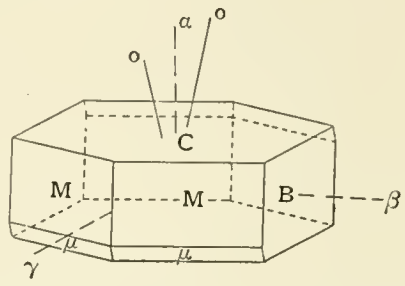

Fig. 616.—Phlogopite, C {001}, B {010}, M {221}, μ {11$\bar{1}$}.

The chief micas are generally separated into the following groups :—

Muscovite (Potash Mica).—$SiO_2 = 42 - 55$, $Al_2O_3 = 20 - 38$, $K_2O = 8 - 12$, $H_2O = 2 - 6$. $2E = 56 - 76°$; $\rho > v$. Axial plane perpendicular to plane of symmetry (Fig. 615).

Muscovite (so named as having been first obtained from Russia) is the commonest mica, and the variety usually contained in granites and mica-schists ; it is generally a pale-coloured, sometimes colourless, mineral with pearly lustre on the cleavage surface ; it occurs generally, like all the other micas, in hexagonal scales—but sometimes in long tapering crystals with rough and irregular side faces, of the habit shown in Fig. 619, always, of course, tending to split across their length.

Lepidolite (Lithia Mica).—$SiO_2 = 49 - 52$, $Al_2O_3 = 26 - 33$, $Li_2O = 1 - 6$, $K_2O = 4 - 10$, $F = 3 - 8$. $2E = 76°$ about ; $\rho > v$. Axial plane perpendicular (also parallel) to plane of symmetry.

Lepidolite is a rose-coloured or lilac mineral rarely found in anything but scaly aggregates ; the name is derived from $\lambda\epsilon\pi\acute{\iota}\varsigma$, a scale ; the colour is probably due to manganese.

Paragonite (Soda Mica).—$SiO_2 = 44 - 50$, $Al_2O_3 = 36 - 40$, $Na_2O = 4 - 8$, $H_2O = 2 - 5$. $2E = 70°$ about ; $\rho > v$. Axial plane perpendicular to plane of symmetry.

Paragonite was the name given to the white schist in which staurolite and kyanite are found at Monte Campione in Switzerland ; the rock was originally supposed to be a talc schist until analysis showed it to be a soda-alumina and not a magnesia silicate. The name ($\pi\alpha\rho\acute{\alpha}\gamma\omega$, I mislead) was given in allusion to this fact.

Phlogopite (Magnesia Mica).—$SiO_2 = 42$, $Al_2O_3 = 12$, $MgO = 27$. $2E = 0° - 20°$; $\rho < v$. Axial plane parallel to plane of symmetry (Fig. 616).

Phlogopite includes the yellow and brown micas, which are, like muscovite, sometimes found in rough prisms or tapering pyramids ;

like muscovite also showing a pearly lustre upon the cleavage face. The mineral is found in metamorphic limestones, sometimes in quite large crystals. It is impossible to draw a sharp distinction between phlogopite and biotite.

Biotite (Ferro-magnesian Mica).—$SiO_2 = 33 - 40$, $Al_2O_3 = 16 - 24$, $Fe_2O_3 + FeO = 10 - 30$, $MgO = 7 - 22$, $K_2O = 1 - 10$, $H_2O = 0 - 10$. $2E = 0^\circ - 20^\circ$; $\rho < v$.

Biotite may, in fact, be regarded as a ferriferous phlogopite; it includes the dark-coloured micas, which are often found, together with the white muscovite, as a constituent of granite, and occurs very commonly in eruptive rocks and in crystalline schists. Some of the biotites have an almost inappreciable axial angle, and the name was originally given to all the magnesia micas in honour of Biot, who (in 1816) found them to be uniaxial.

Zinnwaldite (Lithia-iron Mica).—$SiO_2 = 43 - 46$, $Al_2O_3 = 20 - 22$, $K_2O = 5 - 10$, $Li_2O = 1 - 4$, $F = 5 - 8$. $2E = 50^\circ - 70^\circ$; $\rho < v$. Axial plane parallel to plane of symmetry.

Zinnwaldite was the name applied to the mica of the tin-bearing veins of Zinnwald in Bohemia, and it has generally been found that these lithia-iron micas occur in pegmatitic veins in granites and gneisses, and especially in those which produce cassiterite associated with fluor.

The micas all crystallise in the monoclinic system with angles which nearly correspond to hexagonal symmetry; they have the form of hexagonal tables or columns, whose prism angle is nearly 60°, although the prism is slightly inclined to the base. It might appear more natural to take the prominent prism M of Fig. 615 as {110}, and some authors do so; the prism M is here taken as {221}, because with this notation (110) is a face in the zone CM exactly perpendicular to C, so that the crystal can be referred to three rectangular axes; further, this plane (110) is the common twin plane of the micas, although it is not found as a crystal face. The upper edge CM of Fig. 615 is sometimes replaced by facets of o {112} ($Co = 73^\circ\ 1'$).

In the twin crystals (Fig. 617) one individual lies upon another, the

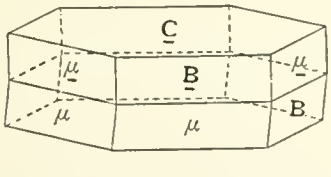

Fig. 617.—Biotite twinned on (110).

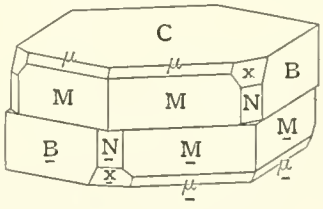

Fig. 618.—Muscovite twinned on (110).

faces C being in contact; the twin plane is parallel to (110), a plane which replaces the edge $M\mu$ and is perpendicular to C. The lower crystal of Fig. 617 corresponds to the upper crystal of Fig. 618, and the twin plane truncates the edge $\mu\mu$ or MM; the twinning may be recognised

by the re-entrant angles between the two individuals. $B\mu = 8° 41'$, $\mu\mu = 17° 22'$. Fig. 617 is biotite from Vesuvius. Fig. 618 represents a little brown crystal of muscovite from the Sulzbachthal, in the Tyrol; here N = (261), $x = (\bar{1}31)$. As compared with Fig. 615 this figure is turned about the a-axis into the position adopted by many authors for mica; μ becomes $\{111\}$ and M becomes $\{221\}$; if the vertical axis c be halved, the indices are $\mu = \{221\}$, M = $\{44\bar{1}\}$ and $a:b:c = 0{\cdot}577:1:1{\cdot}637$; these axes are often adopted.

Owing to twinning, and the rough character of the pyramid faces, most large crystals of mica are rude prisms tapering to one end with very irregular sides (Fig. 619); but owing to its very ready cleavage the mineral is generally found in irregular plates and scales or cleavage flakes.

The crystals sometimes attain large dimensions, and may even measure several feet across, as in the mica of India, Russia, and the United States, used for commercial purposes. All the minerals of this group resemble each other and are distinguished from other minerals by the highly perfect basal cleavage, which permits of their separation into perfectly smooth plates and scales of extreme thinness (a property utilised to produce the $\frac{1}{4}$-wave-length mica plate, p. 170), and also by their "elasticity," so that cleavage flakes are not pliable, like gypsum, but spring back after being bent.

Some of the micas are nearly or quite uniaxial, while others are biaxial with a large angle, but they are all alike in the sign and magnitude of their double refraction, which is always negative and very strong, while the refractive power is weak. The coloured micas are strongly pleochroic, the rays which vibrate parallel to the cleavage being far more absorbed than those which vibrate perpendicular to it; hence any section of mica cut across the cleavage appears darkest when its cleavage lines are parallel to the shorter diagonal of the polarising nicol prism. In rock sections this readily distinguishes a cross section of mica from a prism of tourmaline, for the latter appears darkest when its prism edge is parallel to the longer diagonal of the polariser (pp. 176, 177, Figs. 361, 362.) Even where there is no visible crystalline contour the monoclinic nature of a mica crystal can be proved by the simple examination of a cleavage flake; for whether the plate be uniaxial or biaxial it will be found that the optic axis, or the acute bisectrix, is never rigidly perpendicular to the cleavage plane, but makes with the normal to that plane an angle which may vary from a few minutes to eight degrees, and lies in the plane of symmetry (B).

With change of temperature the inclination of the acute bisectrix to the cleavage plane is found to change slightly, while it remains in the plane of symmetry, and this property enabled Hintze to prove that a very perfect reddish-brown crystal of Vesuvian biotite, the measurements of which made it appear hexagonal or orthorhombic in symmetry, was really monoclinic, since in those systems the optic axis or the acute bisectrix would remain perpendicular to the basal plane at all temperatures, whereas a change of more than 30′ was observed at 178°.

The position of the plane of symmetry may be found in any cleavage plate of biaxial mica by means of the "percussion figure." This figure, as explained on p. 109, consists of a six-rayed star in which the rays intersect at angles of 60°; one of them (usually better defined than the others) being parallel to (010). Now one of these rays will be found to be perpendicular or parallel to the plane of the optic axes; this particular ray must therefore be the trace of the plane of symmetry, and in the first case the cleavage flake is said to belong to a "mica of the first class" (Macrodiagonal mica), in the second case to a "mica of the second class" (Brachydiagonal mica).

The figure ("pressure figure") produced by pressing upon a cleavage plate with a *blunt* point is a six-rayed star whose rays bisect the angles between those of the percussion figure and indicate the existence of gliding planes parallel to the faces of various pyramids; these have been referred to the forms $\{\bar{2}05\}$ and $\{135\}$.

The "asterism" shown by some mica, which is particularly common in phlogopite, is probably due to fine inclusions arranged along the glide-planes. A spot of light viewed through a cleavage flake of such mica appears as a six-rayed star; or sometimes as a twelve-rayed star; or may give six or twelve distinct images of the spot. Inclusions of various minerals in mica are very common; they are usually in the form of very thin plates lying parallel with the cleavage of the mica. Even tourmaline (as in the muscovite of Paris in Maine) and garnet (in the muscovite of Haddam, Connecticut) occur thus as transparent flakes or films. Beautiful translucent brown and red dendritic inclusions of hexagonal symmetry occur in the muscovite of Pennsbury (Pennsylvania). These probably consist of hæmatite and göthite.

As regards their chemical composition the micas are extremely various and difficult to classify; there can be little doubt that they will ultimately be referred to certain isomorphous series, like the felspars or the garnets, but at present it is impossible to assign a general formula with any certainty to the whole group or even to any section of the group; an attempt is made on p. 543.

As constituents of rocks they are roughly divided into dark micas and white micas. The dark ferro-magnesian micas are generally uniaxial, or nearly so, and are classed together under the name of biotite; the white potash micas are generally biaxial with an apparent angle of about 60°, and are classed together under the name of muscovite.

Some of the dark micas have a composition approximately represented by the formula $(K, H)_2(Mg, Fe)_2Al_2(SiO_4)_3$, in which the oxygen ratio is that of an orthosilicate. Some of the light micas have nearly the composition $H_2KAl_3(SiO_4)_3$. But there are other varieties which cannot be regarded as orthosilicates; a pure lime-alumina silicate known as margarite, and sometimes referred to the mica group, is apparently to be denoted by the formula $H_2CaAl_4Si_2O_{12}$. (See, however, below, p. 500.) The water which is contained in the micas is mostly given off at a high temperature, and must be regarded as water of constitution, although in many specimens there may be a certain amount of water held mechanically

between the fine cleavage laminæ, which will be given off at 100°. In what manner the fluorine enters into the composition of a mica, how the hydrogen is combined, how the excess or deficiency of oxygen above or below the orthosilicate ratio is to be accounted for, and of what silicic acids these minerals are salts, are difficulties which have not yet been satisfactorily solved.

For ordinary purposes the group is most conveniently divided as above into :—

Ferro-magnesian micas—Biotite.
Alkali micas—Potash mica—Muscovite.
Soda mica—Paragonite.
Lithia mica—Lepidolite.

(And many authors add
Lime mica—Margarite).

Varieties which are rich both in lithium and iron are distinguished as zinnwaldite ; and those which contain much magnesia and little iron are known as phlogopite.

Many attempts have been made to determine compounds of which these may all be regarded as isomorphous mixtures.

Tschermak's theory of the mica group is as follows :—

Those alkali micas, known as damourite, in which the proportion of Al : Si is 1 : 1, may be represented by the formula $HAlSiO_4$, where H can be replaced in different proportions by K, Na, and Li ; further, the ferro-magnesian micas may be represented as molecular compounds of this silicate with the salt Mg_2SiO_4 ; and, lastly, the remaining members of the group, in which the oxygen ratio is not that of an orthosilicate, may be regarded as molecular compounds of one or both of the above with salts of a hypothetical silicate $H_4Si_5O_{12}$; in those micas which contain fluorine, this element is supposed to replace hydroxyl, (OH), or oxygen.

The three isomorphous constituents which form the basis of the whole mica group are then

$$K = H_6Al_6(SiO_4)_6.$$
$$M = Mg_{12}(SiO_4)_6.$$
$$S = H_8Si_{10}O_{24}.$$

The first of these represents the pure potash and soda micas (damourite and paragonite), while M is a polymer of olivine. The hypothetical compound S is obtained from a consideration of the alkali micas, in which Al : Si = 2 : 3 ; these are classed by Tschermak under the name phengite, and their analyses lead to the formula

$$L = H_6Al_4Si_6O_{21}.$$

Further, it is found that the lithia micas may be referred to the same general formula L in which fluorine replaces O or OH ; thus—

$$\text{Lepidolite} = Si_6Al_4K_2Li_2H_2F_2O_{20}.$$
$$\text{Zinnwaldite} = Si_6Al_4K_2Li_2F_4O_{18}.$$

The phlogopites may then be regarded as mixtures of L, M, and the biotites as mixtures of K, M. Now of the three compounds K, M, L, the first two are alike in having the ratio of O to the other elements = 4 : 3. In order to reduce L to the same form it must be subdivided into

$$Si_4H_4Al_4O_{16} + Si_2H_2O_5 \text{ or } 4HAlSiO_4 + Si_2H_2O_5.$$

Replacing the latter of these two members by the molecule $Si_5H_4O_{12}$ (which will equally well correspond to the analyses within errors of observation), it is possible to regard L as a mixture of K and S. The three compounds K, M, S are now alike in the ratio 4 : 3 of oxygen to the other elements, and may therefore, according to Tschermak, be supposed capable of uniting as isomorphous compounds.

Clarke's theory of the mica group starts from the idea that the natural silicates are probably salts of simple constitution; he therefore regards all the micas as substitution derivatives of a normal orthosilicate $Al_4(SiO_4)_3$. One, two, or three atoms of Al may be replaced by equivalent proportions of univalent alkali metals, or by the divalent metals Mg, Fe″, or by Fe‴. In those micas which contain fluorine, the univalent groups MgF or AlF_2 are supposed to act as replacing radicles; into those in which there is defect of silica the univalent groups AlO or MgOH are supposed to enter; in those which present an excess of silica the orthosilicic acid H_4SiO_4 is partially replaced by the tetrabasic acid $H_4Si_3O_8$ (*cf.* the felspar group, p. 453).

Hence all the micas may be expressed as isomorphous mixtures of salts varying in composition from $Al_3R'_3(SiO_4)_3$ to $AlR'_9(SiO_4)_3$ and from $Al_3R'_3(Si_3O_8)_3$ to $AlR'_9(Si_3O_8)_3$.

These views illustrate the difficulty of determining with certainty the relationship between the different micas, and we shall here be content to classify them by their general composition according to the table on p. 470, leaving margarite for consideration apart. Rammelsberg regarded the micas as partly orthosilicates and partly mixtures of orthosilicates with metasilicates. Some of the lepidolites appear to be referable to simple metasilicates.

Some writers classify the micas according to the presence or absence of fluorine.

Many authors (following Tschermak) divide them into the two groups: "micas of the first class," in which the optic axial plane is *perpendicular* to the plane of symmetry and $\rho > v$, and "micas of the second class," in which the axial plane is *parallel* to (010) and $\rho < v$. To the first class belong almost all the alkali micas; to the second class belong the ferro-magnesian micas, phlogopite and zinnwaldite. Those anomalous biotites which do not conform to this rule are placed in the first class under the name "anomite." A great convenience of this classification is that it is always possible, by means of the percussion figure and microscope, to refer any cleavage flake of mica to one of these two classes.

The micas are of very widespread occurrence. Muscovite is an essential constituent of most granites, and occurs in some of the quartz

porphyries, but is not found in the volcanic lavas; the best specimens of mineral collections are those in which the muscovite forms large platy crystals in the granites or is crystallised out in druses of that rock; it is also found as an important constituent of the crystalline schists, and in many metamorphic rocks, especially where slates and other sedimentary materials have been subjected to regional metamorphism. As regards the other alkali micas, lepidolite is also found in granites in pegmatite veins associated with tourmaline and other minerals which contain fluorine; paragonite is comparatively rare, and is almost entirely confined to the crystalline schists.

Zinnwaldite almost always accompanies the tin ore of certain granites, where it is also associated with tourmaline. Biotite is, like muscovite, characteristic of the granites, but also of many volcanic rocks, of the crystalline schists, and of the crystalline limestones and contact zones between granite and sedimentary rocks, and is also a constituent of the minette of the Vosges.

The isomorphism of the micas is indicated not only by the close resemblance of their form and cleavage but also by their tendency to grow together in regular positions; thus crystals are common in which a core of biotite is surrounded by and passes into a shell of muscovite. Again, the pink lepidolite, which is found at Schüttenhofen in Bohemia, in a pegmatite traversing limestone, frequently encloses greenish muscovite, the cleavage running right through the compound crystal; the two minerals appear to be generally twinned together; the same mode of growth is also to be found in the very similar occurrence of lepidolite at Auburn (Maine).

Mica was not separated from talc and gypsum (which it only resembles in cleavage) until the end of the last century. Klaproth (1810) distinguished the magnesia micas, and they received the name biotite in 1816. The lepidolite from Moravia was in the last century distinguished on account of its colour; the presence of lithium was first proved in 1820.

Heated in the closed tube all the micas yield a little water; lepidolite and zinnwaldite give the red lithium colour to flame and are readily fusible (2), lepidolite to a gray, and zinnwaldite to a dark globule. Muscovite and paragonite are almost unacted upon by strong boiling sulphuric acid; biotite and phlogopite are partially decomposed; these four minerals are only slightly fusible. Most micas, like other minerals containing F and OH, yield acid water in the closed tube.

Chromium mica (fuchsite) may be distinguished by its brilliant green colour. Manganese mica (*e.g.* the so-called alurgite of Piedmont) may be distinguished by its deep red colour.

Some Noteworthy Localities:

Muscovite.—Muscovite occurs in large plates at many places in the albitic granite of the Urals, notably at **Alabaschka** near Mursinka, where it is associated with orthoclase, albite, and smoky quartz.

Very large transparent sheets of muscovite are obtained from **Solovetsk Island** (Archangel).

Thin transparent sheets of this mineral were formerly used largely for window glass in houses and also in the Russian ships of war (as being less liable to break with the concussion of cannon); it was commonly known as "muscovy glass." Large plates for commercial use are now obtained from **Bengal** and from the granite of **Brazil**; it is used for insulating purposes in electric machinery, for lantern glasses, and for lamp chimneys (often wrongly called talc); it was formerly known as "glacies Mariæ" (or Frauenglas), because the scales were used as spangles to decorate statues of the Virgin.

Lepidolite.—Lepidolite is found at **Rozena** (Moravia) in a broad band at the junction of a pegmatitic vein-granite with a granulitic gneiss on the Hradisko Mountain. The lepidolite occurs as scaly masses of a delicate peach-red colour, and is associated with topaz, tourmaline, etc.

This lepidolite is to be found in all collections; it is a very pure lithia mica containing 5·88 per cent of Li_2O, and is almost the only source of the lithium used for medicinal and other purposes.

The large hexagonal plates of mica found in "vughs" or druses of many of the tin-bearing granites of **Cornwall** are to be referred to this species or to zinnwaldite. A typical lepidolite in silvery plates, associated with quartz, topaz, and cassiterite, is found in the granite of **St. Michael's Mount** (Marazion).

Phlogopite.—In the granular white dolomite of **Campolongo** (St. Gothard, Switzerland), associated with greenish tourmaline, is found a typical phlogopite, which occurs in pale yellowish-brown lustrous scales and hexagonal plates.

Phlogopite occurs at **Oxbow** (Jefferson County, New York) (Fig. 619), in a white crystalline calcite which is mixed with abundant greenish serpentine. The phlogopite is in plates or long rude crystals which are of a light reddish-brown colour on their cleavage surfaces. In other parts of New York and in Canada (**Burgess**, Ontario) a similar phlogopite is found, also in calcite associated with serpentine.

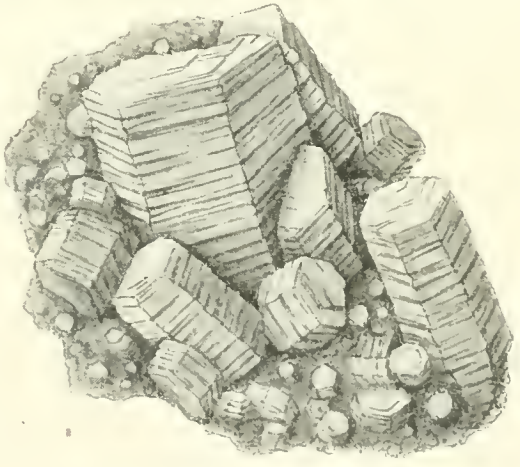

Fig. 619.—Phlogopite from New York.

Biotite.—The best crystallised examples of mica to be found are those which occur in the druses of the limestone blocks ejected from **Monte Somma** (Vesuvius). This, which is known by the name of "meroxene," is a variety of biotite, being a potash-magnesia mica containing about 7 per cent of FeO. The brilliant little crystals in the druses vary from colourless to green, yellow, brown, black or red; they may be either thin plates, thick tables, or long tapering prisms, and their prism and pyramid faces are often perfectly smooth and lustrous.

Accompanied by brilliant crystals of augite, olivine, humite, etc., they constitute very beautiful specimens, and are to be found in most collections.

The sanidine bombs of Monte Somma also contain scaly aggregates of a dark-coloured biotite.

Biotite is found in enormous dark brown sheets in a coarsely granular calcite on the **River Sludianka** near Lake Baikal (Siberia). This mica is the typical anomite of Tschermak, being a biotite which belongs to the first class, having its axial plane perpendicular to the plane of symmetry.

Zinnwaldite.—In the stanniferous lodes which traverse a coarsely granular greisen at **Zinnwald** (Bohemia) are found hexagonal plates, sometimes of considerable size, of a gray (to green, brown, or yellow) zinnwaldite, accompanied by fluor and cassiterite, and sometimes scheelite. The mica is generally crystallised upon quartz, and the plates are sometimes of considerable thickness.

Dark green plates of zinnwaldite, found in the stanniferous lodes in the granite and greisen of **Altenberg** (Saxony), have been long known as "Rabenglimmer."

Much of the mica which accompanies cassiterite and tourmaline in the granite of **Cornwall** is doubtless to be referred to zinnwaldite, although some is lepidolite proper.

TOURMALINE

Tourmaline. — Borosilicate of aluminium and alkalies with iron and magnesium, containing also water (OH) and fluorine. Hexagonal; symmetry, ditrigonal polar.

$$a : c = 1 : 0{\cdot}4477.$$

$$a = \{1\bar{1}0\},\ m' = \{1\bar{2}1\},\ m = \{2\bar{1}\bar{1}\},\ \mathrm{R} = \{100\},\ e = \{110\},\ o = \{\bar{1}11\},$$
$$x = \{\bar{2}11\},\ u = \{30\bar{2}\},\ y = \{3\bar{1}\bar{1}\},\ \mathrm{C} = \{111\}.$$

$$\mathrm{RR}\ (100) : (010) = 46^\circ\ 52',\ \mathrm{CR}\ (111) : (100) = 27^\circ\ 20',\ oo\ (11\bar{1}) : (1\bar{1}\bar{1}) = 77^\circ\ 0',$$
$$\mathrm{Co}\ (111) : (\bar{1}\bar{1}1) = 45^\circ\ 57',\ \mathrm{R}x\ (100) : (\bar{2}11) = 21^\circ\ 41',\ uu\ (30\bar{2}) : (3\bar{2}0) = 66^\circ\ 1',$$
$$ee\ (110) : (101) = 25^\circ\ 2'.$$

Cleavage R, a, imperfect. Brittle. Fracture, sub-conchoidal. H = 7; G = 3·1. Black (brown in thin splinters). Streak, colourless. Lustre, vitreous. Translucent; $\omega = 1{\cdot}64$. Birefringence, strong, negative; $\omega - \epsilon = 0{\cdot}017$. Fusible. Insoluble in acids. Strongly pyro-electric and pleochroic.

With the above description compare crystals from **Mursinka** in the Urals.

Tourmaline, like mica, varies greatly in appearance and colour, on account of its wide variations in chemical composition. An analysis of the black tourmaline from Mursinka yielded $SiO_2 = 34{\cdot}88$, $B_2O_3 = 8{\cdot}94$, $Al_2O_3 = 34{\cdot}58$, $FeO = 14{\cdot}40$, $MgO = 1{\cdot}32$, $Na_2O = 2{\cdot}70$, $H_2O = 2{\cdot}87$, $F = 0{\cdot}51$, with small proportions of TiO_2, MnO, CaO, and K_2O. This and similar tourmalines correspond approximately to $H_6Na_2Fe_4B_6Al_3Si_{12}O_{63}$.

Tourmaline is of some importance as a rock-forming mineral; it is also especially interesting as one of the best and most conspicuous

examples of polar symmetry (hemimorphism); the phenomenon of pyro-electricity was discovered in tourmaline, and its remarkable absorption has given it a special value as a material that can be used for producing plane-polarised light.

The name tourmaline appears to be of Cingalese origin; in the middle ages, and even at the present day among miners, ordinary black tourmaline was known by the name of "schorl," a word whose origin is doubtful.

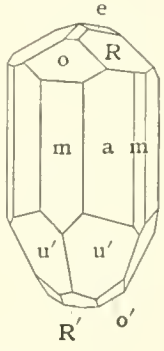

Fig. 620.—Tourmaline, R {100}, *o* {$1\bar{1}1$}, *e* {110}, *m′* {121}, *m* {$2\bar{1}1$}, *a* {$11\bar{2}0$}, R′ {$01\bar{1}0$}, *o′* {$11\bar{1}$}. *u′* {$03\bar{2}$}, from Gouverneur, New York.

Doubly terminated crystals are rare; they are found especially at localities where the mineral has crystallised out freely in limestone, or in gneiss, or granulite. The microscopic crystals found in many sands may be recognised by their form (Fig. 620); the more familiar museum specimens of tourmaline found in granite, etc., are generally attached by an end; this is equally true of many minerals of polar symmetry. It is possible that the symmetry may be polar trigonal, and not ditrigonal; for several forms such as *x* and *u* have been observed to present only three faces at one end of the crystal; but the usual development of {$10\bar{1}$} as a hexagonal, and only of {$2\bar{1}\bar{1}$} as a trigonal prism, points to ditrigonal symmetry.

All coloured tourmalines possess a well-marked pleochroism; in black varieties ω = green or blue, ϵ = brown or red; it is less con-

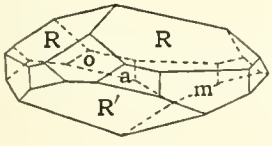

Fig. 621.—Tourmaline, R {100}, *o* {$1\bar{1}1$}, *m* {$2\bar{1}1$}, *a* {$11\bar{2}0$}.

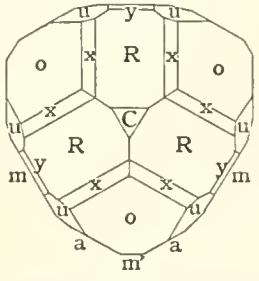

Fig. 622.—Tourmaline, analogous end; from Pierrepont, New York.

spicuous in the yellow, brown, green, or red crystals, but in all of them the absorption of the ordinary ray is much greater than that of the extraordinary; this difference is so considerable in some of the dark brown crystals that a section parallel to the optic axis transmits practically only the extraordinary rays (p. 125) and can be used as a polariser or analyser.

The interference figure of a crystal section can be very well seen by placing it between two such plates, mounted in wire rings, kept together by a wire clip, and held close to the eye; this device is known by the name of the "tourmaline tongs."

Sections of tourmaline suitable for this purpose are extremely rare,

but when good and only faintly coloured, they are to be preferred even to a nicol prism.

The pyro-electric property, which was first observed at the beginning of the eighteenth century, on the red crystals brought from Ceylon, can be very easily shown by means of Kundt's dusting method. The end which becomes negatively electrified during cooling (the analogous end) generally has the faces of R {100} over the faces of the trigonal prism m $\{2\bar{1}1\}$; at the antilogous end the faces of R (if present) are over the edges of the same prism. Some apparent exceptions to this rule may be explained by the presence of the inverse prism m' $\{1\bar{2}1\}$ instead of the direct form. The basal plane C is usually at the analogous end. The antilogous end is sometimes acute, owing to the development of $\{03\bar{2}\}$ and other pyramidal forms; good examples of this habit are found among the brown crystals from Gouverneur (New York).

Characteristic features in the aspect of a tourmaline crystal, even when it has no terminations, are (1) the triangular cross section, due to the predominance of the trigonal prism m' or m, and (2) the vertical striations of the prism faces; these and the absence of cleavage serve to distinguish schorl from black hornblende and other minerals which it may resemble.

Juxtaposition twins of tourmaline are almost unknown, but the alternation of analogous and antilogous patches on cross sections points to supplementary twinning, similar to that of hemimorphite (p. 90).

The chemical composition of tourmaline has been, and still is, the subject of much discussion.

Rammelsberg suggested that all the tourmalines can be represented as derived from the acid H_6SiO_5, in which H_3 can be replaced by Al and B; H_2 by Fe, Mg, Mn, Ca; H by Na, K, Li.

Riggs proposed the formula $R_9 . BO_2 . (SiO_4)_2$, which was adopted by Jannasch and Kalb, and by Groth, in the form $R_6 . AlO . BO . (SiO_4)_2$.

According to Clarke the composition may be represented by $H_{14}Al_5B_3Si_6O_{31}$, in which all the fourteen hydrogen atoms are replaceable by bases.

According to Penfield and Foote, the formula is $H_{11}Al_3B_2Si_4O_{21}$, in which two hydroxyl groups are associated with the boron, and the remaining nine hydrogen atoms are replaceable by bases.

A classification by composition and colour like that adopted above for the micas is scarcely possible in the case of tourmaline; but the alkali-tourmalines are generally red or green; the magnesia-tourmalines brown; the ferriferous tourmalines black. Transparent crystals are sometimes banded with zones of different colours, or are differently coloured at the two ends (*e.g.* those from Maine, U.S.A, and Brazil).

Perfectly colourless tourmaline has been found and is distinguished as "achroite"; crystals of achroite from Elba are an alkali tourmaline ($Na_2O = 2$, $K_2O = 1{\cdot}30$, $Li_2O = 1{\cdot}22$) free from iron.

Tourmaline possesses a sufficiently high specific gravity, hardness,

and refractive index to make it an excellent gemstone; red varieties are known as "rubellite"; the indigo-blue variety as "indicolite." The mineral may be conveniently distinguished from other gemstones by the use of a heavy liquid (G = 3), and of the total reflectometer ($\omega = 1{\cdot}6$).

The best gem tourmalines are derived from the sand washings in Ceylon.

Tourmaline fuses (about 5-6) to a globule or a slag according to its composition; the boron, which it always contains, may be recognised by the green colour imparted to flame when the mineral, mixed with potassium bisulphate and fluor, is heated on platinum wire. Some varieties, especially the magnesia- and lithia-tourmalines only fuse with difficulty upon the edges.

Some Noteworthy Localities:

Elba.—In the granite of **San Piero** are veins which contain abundant tourmaline associated with white orthoclase, silvery mica, white and rose-coloured beryl, albite, quartz, and yellowish-red garnets. Some of the tourmaline is nearly black, especially at the edges of the veins; but some of the druses contain beautiful rose-coloured crystals; these are terminated by the basal plane C, which is dull at the analogous and bright at the antilogous end; the crystals are never doubly terminated and generally present the analogous end.

This granite also yields green crystals, and the colourless achroite, and also prisms showing alternating bands of red and green.

Campolongo (Switzerland).—The white granular dolomite, already mentioned as the matrix of corundum, yields also green prisms of tourmaline with alternate edges truncated by small faces of *m*, terminated by *o*, the edges of which are truncated by small faces of R. Silvery mica, diaspore, calcite, red and blue corundum are the associated minerals.

Ural Mountains.—At **Schaitanka** near Ekaterinburg, in a coarse granite, associated with albite, smoky quartz, green mica and pink lepidolite, are found in the druses beautiful red crystals of rubellite, striated prisms (*a*) terminated by C at the analogous, and by R at the antilogous end. At **Mursinka**, about thirty miles north, in the albitic granite which produces topaz and beryl, is found fine black tourmaline noteworthy as often doubly terminated; R is bright at the analogous, and dull at the antilogous end.

New York.—At **Gouverneur** in St. Lawrence County are found large brown crystals associated with apatite and scapolite in a granular limestone. In these the polar character is very well marked by the acute termination of the antilogous pole (Fig. 620).

At **Pierrepont** the limestone contains fine black tourmaline associated with dark phlogopite, pyroxene and rounded quartz.

Devonshire and Cornwall.—At **Chudleigh** near Bovey Tracey in Devonshire a granite quarry formerly yielded large crystals of black tourmaline associated with large gray opaque prisms of apatite. The

tourmaline is in prisms, sometimes short, as in Fig. 621, *a* bright, *m'* dull; these are remarkable in having R above the faces of *m'* at the *antilogous* end, so that *m'* is evidently the trigonal prism {121} complementary to the more usual one of Fig. 621. The latter also occurs on these crystals. The faces R are usually rough and rounded at the analogous end.

In many localities in Cornwall the granite contains black tourmaline; the common schorl, especially in the decomposed granite of **St. Austell**, which yields china clay, is in fine needles, which often assume the form of a fibrous or silky mass.

THE SCAPOLITE GROUP

In connection with the foregoing fluoriferous silicates, mention may here be made of a group of minerals some of whose members contain chlorine as an essential constituent.

Scapolite (or wernerite) is a tetragonal mineral, found in large opaque white crystals with augite and hornblende in limestone at Arendal in Norway. Here and at other localities the mineral is usually somewhat altered, but may be recognised by its tetragonal form (Fig. 623) ($r = \{111\}$, $h = \{210\}$) and two sets of rectangular cleavages A*m*. A similar mineral is found in the metamorphic rocks, especially the limestone and magnetite of Finland, Sweden, and the United States, and when massive resembles felspar in appearance. In composition it is an alumo-silicate of calcium containing also alkalies, water, and some chlorine. As the proportion of silica increases the proportion of alkalies and chlorine increases also.

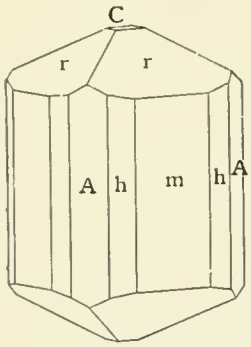

Fig. 623.—Scapolite, A {100}, *m* {110}, *h* {210}, *r* {111}, C {001}.

In the ejected limestone blocks of Monte Somma (Vesuvius), are found small limpid glassy tetragonal prisms having the same angles and cleavage; these are known as **meionite** and have the composition $Ca_4Al_6Si_6O_{25}$ ($SiO_2 = 40{\cdot}5$). In the trachyte of Monte Somma are found similar crystals containing about 55 per cent of silica, which are distinguished as **mizzonite**. Finally, in the volcanic piperno of Pianura near Naples occur crystals belonging to the same group, and approximating to the composition $Na_4Al_2Si_9O_{24}Cl$, which requires $SiO_2 = 63{\cdot}9$, $Cl = 4{\cdot}2$. These are known as **marialite**.

It has been suggested by Tschermak that all the minerals of the scapolite group may be represented as mixtures in varying proportions of meionite (Me) and marialite (Ma); the common scapolite approximates to Me_3Ma.

SECTION XXII

THE ZEOLITES

UNDER the name zeolites are classed together a number of hydrated silicates of alumina and alkalies, most of which also contain lime; their water of crystallisation is very loosely held, and they intumesce before the blowpipe; the name zeolite ($\zeta\acute{\epsilon}\omega$ = I boil) was given in allusion to this property. They are found, often beautifully crystallised, as decomposition products lining cavities in altered igneous rocks, having mainly been derived from the felspar; in fact some of the zeolites have practically the composition of hydrated felspar; thus, stilbite corresponds to the albite formula with 6 molecules of water, and with Ca in place of Na_2; thomsonite corresponds to anorthite with $2\frac{1}{2}$ molecules of water.

They are mostly fusible and decomposed by acids, and have a vitreous or pearly lustre and a specific gravity about 2.

THE STILBITE GROUP

Stilbite.—Hydrated silicate of calcium and aluminium; $CaAl_2Si_6O_{16}.6H_2O$; $CaO = 8{\cdot}94$, $Al_2O_3 = 16{\cdot}31$, $SiO_2 = 57{\cdot}51$, $H_2O = 17{\cdot}24$. Some Ca is almost always replaced by Na_2. Monoclinic (pseudorhombic).

$$a : b : c = 0{\cdot}7623 : 1 : 1{\cdot}1940. \quad \beta = 50^\circ\ 50'.$$
$$C = \{001\},\ B = \{010\},\ m = \{110\}.$$
$$mm\ (110) : (1\bar{1}0) = 61^\circ\ 10',\ Cm\ (001) : (110) = 57^\circ\ 4'.$$

Twinned on C. Cleavage B, perfect. Brittle. Fracture, uneven. $H = 3\frac{1}{2}$; $G = 2{\cdot}2$. White. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1{\cdot}498$. Birefringence rather strong, negative; $\gamma - \alpha = 0{\cdot}006$. Axial plane B. Acute bisectrix inclined at 85° to the normal of C, and at 34° 10′ to the normal of A (100). $2E = 51\frac{1}{2}^\circ$; $\rho < r$. Fusible ($2\frac{1}{2}$). Decomposed by hydrochloric acid.

With the above description compare crystals from **Talisker** in Skye.

Stilbite is found in beautiful crystals in the amygdules of trap rocks in several parts of the world; they resemble a combination of an orthorhombic pyramid with (100) and (010), but are in reality interpenetrant twins, a combination of CB*m*, united by twinning on C, as shown in Fig. 624.

The pearly lustre and perfect cleavage of the face B is very char-

acteristic, and the crystals are usually plates flattened parallel to this face. There is also an imperfect cleavage parallel to C. The extinction angle on a cleavage flake B with regard to the basal plane C is 5°, and the flake is perpendicular to the third mean line; the twinning is generally recognisable in a cleavage flake by division into sectors whose extinction directions are inclined at 10° to each other.

Crystals having the form of Fig. 624 are often aggregated into bundles or sheaves, as shown in Fig. 625.

At some localities the mineral is of a brick-red colour.

Before the blowpipe, stilbite fuses to a white enamel after intu-

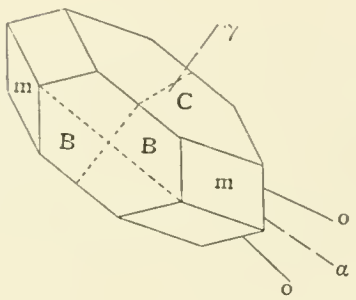

Fig. 624.—Stilbite, B {010}, *m* {110}, C {001}, twinned on (001).

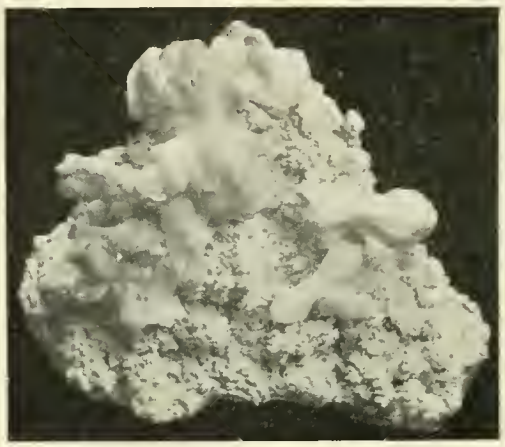

Fig. 625.—Stilbite from Berufjord, Iceland (British Museum).

mescence; it is decomposed by hydrochloric acid, without gelatinisation, but with separation of slimy silica.

Some Noteworthy Localities:

Poonah (India).—Large salmon-coloured crystals of tabular habit are found in amygdules of the trap of this district associated with large colourless crystals of apophyllite, and striated prisms of scolecite; the smaller amygdules are sometimes filled or lined with a green earthy mineral which appears to be an impure stilbite.

Scotland.—Amygdules in the basalt of **Talisker** in Skye contain crystals of the habit of Fig. 624 situated upon a finely fibrous mealy zeolite (mesolite).

At **Campsie** and **Kilpatrick** in Stirlingshire amygdules of the decomposed basalt are lined with fine red crystals of stilbite associated with heulandite of the same colour.

Faröe Islands.—The basalt contains cavities lined with fine white crystals of tabular stilbite accompanied by apophyllite and a fibrous or spheroidal thomsonite known as "faröelite."

Fig. 625, from a photograph of a specimen from Berufjord in Iceland, illustrates the manner in which stilbite often occurs aggregated into sheaves which spread out at the two ends. Stilbite has already been mentioned as encrusting the Iceland spar of Eskifjördhr (p. 400).

Phillipsite may perhaps be $CaAl_2Si_5O_{14} . 5H_2O$, in which variable proportions of Ca are replaced by equivalent proportions of K and Na (see, however, p. 543); it has nearly the same form as stilbite: $mm = 60° 42'$, $Cm = 60° 50'$. The crystals present a singular cruciform appearance, Fig. 626, and simulate tetragonal symmetry; that they are twins is easily seen from the stellate shape and re-entrant angles of the terminations, and from the striæ. Each such crystal is due to the interpenetration of two complex crystals similar to Fig. 624 of stilbite; each arm of the cross consists of two or four individuals twinned together on C, and the two arms are united by twinning on (011); the angle 001 : 011 = 46° 2′, so that the two arms are nearly at right angles to each other, and if the re-entrant angle is small the whole group may present the appearance of a tetragonal prism and pyramid. The crystals cleave parallel to B (also C), but not nearly so distinctly as stilbite and heulandite; B is perpendicular to an obtuse negative bisectrix. Phillipsite generally occurs in colourless glassy crystals lining cavities in basalt with other zeolites. Before the blowpipe it fuses to a white enamel, but without the lively intumescence of stilbite.

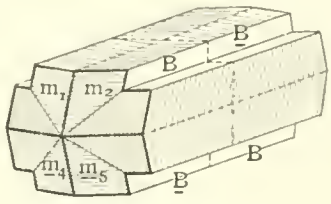

Fig. 626.—Phillipsite.

Harmotome may be the compound $BaAl_2Si_5O_{14} . 5H_2O$, corresponding to phillipsite (see p. 543). In crystalline form, habit, and twinning

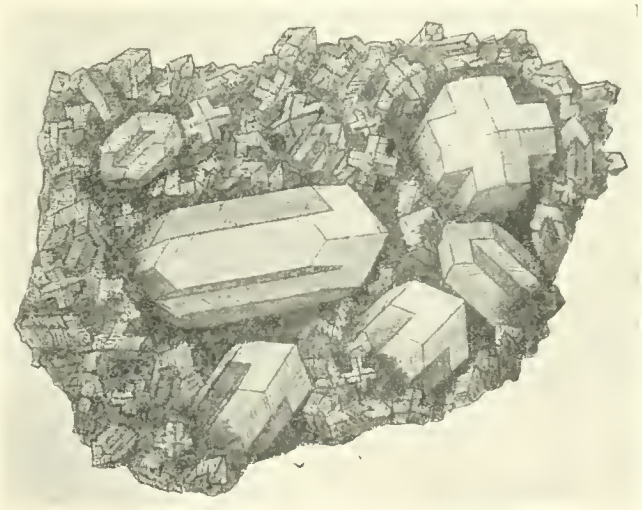
Fig. 627.—Harmotome from Andreasberg.

it very closely resembles that mineral, and is also found in the cavities of basalt. It is somewhat denser (G = 2·5) than phillipsite (G = 2·2), and is fusible with greater difficulty, and without exfoliation.

Among typical localities of harmotome may be mentioned Andreasberg in the Harz, where it occurs in white crystals with calcite, quartz, galena, etc., as a constituent of the metalliferous veins which traverse the slate (Fig. 627). At Strontian in Argyllshire fine transparent crystals occur with calcite and barytes in veins of the granite

THE HEULANDITE GROUP

Heulandite, $H_4CaAl_2Si_6O_{18} . 3H_2O$ (monoclinic), has nearly the same composition as stilbite, differing only in the proportion of water; it occurs under the same conditions, often together with stilbite, and much resembles it in appearance; the crystals, like those of stilbite, are sometimes colourless or white, but sometimes red, and possess a similar perfect cleavage; they have a characteristic coffin-shaped habit, as shown in Fig. 628. The perfect cleavage is parallel to B {010} and has a pearly lustre even more pronounced than that of stilbite: C = {001}, s = {201}, t = {201}. Ct (001) : (201) = 63° 40′, Cs (001) : (2̄01) = 66° 0′.

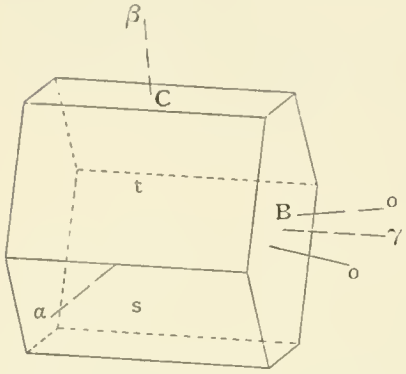

Fig. 628.—Heulandite, B {010}, C {001}, t {201}, s {201}.

As is seen from Fig. 628, the cleavage B is perpendicular to the acute positive bisectrix (2E = 50° about), and this affords a ready means of distinguishing heulandite from stilbite; in most respects the two minerals are closely alike.

The name stilbite was given from the word στίλβω, I shine, and heulandite is named after a well-known mineral collector; in German text-books and treatises the mineral here called stilbite is named desmine, and our heulandite is sometimes called stilbite.

At Strontian, the original locality for strontianite, are found also gray pearly crystals of **brewsterite**, a mineral having the formula of heulandite, in which Ca is partially replaced by Ba and Sr; it is isomorphous with heulandite.

THE CHABAZITE GROUP

Chabazite, $CaAl_2Si_4O_{12} . 6H_2O$, in which varying proportions of Ca are replaced by Na_2 and K_2, crystallises in rhombohedra of 85° 14′, and occurs in glassy white or pink crystals. The rhombohedron is almost always striated parallel to its edges, and the crystals are usually interpenetration twins united by hemitropy about the principal axis, as shown in Fig. 629. This is so characteristic that chabazite may generally be recognised by the twinning which makes the crystals somewhat resemble fluor; the striations, and a fair cleavage parallel to the rhombohedron, distinguish it from that mineral.

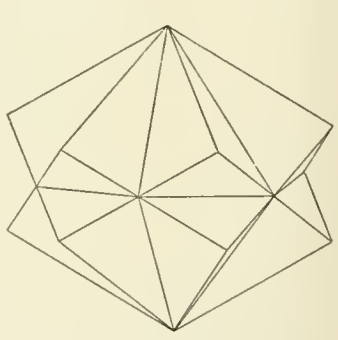
Fig. 629.—Chabazite, {100}, twinned on the axis [111].

Beautiful white crystals of chabazite have been found in cavities of the basalt of the Giant's Causeway.

Flat rhombohedra, with {110} predominant, showing the same inter-

penetration-twinning, have been found at several localities and have received the name "phacolite"; these are often lenticular (φακὸς, a lentil). Beautiful glassy crystals of this variety have been found in cavities of a compact basalt at Richmond in Victoria, and are associated with phillipsite, analcite, calcite, sheaf-like stilbite, and radiating bundles of a brown ferriferous calcite. This variety is sometimes known as "seebachite."

Gmelinite is the name given to the corresponding sodium compound $Na_2Al_2Si_4O_{12} . 6H_2O$, isomorphous with chabazite and twinned in the same manner. Owing to the development of the inverse rhombohedron {122}, together with R {100} (*cf.* Fig. 156, p. 65), the crystals resemble hexagonal bipyramids, but the twinning may be detected by the re-entrant angles upon their edges.

Fine pink rhombohedra of this mineral occur, with pink phillipsite, natrolite and analcite, in cavities of the basalt of Magee Island (Antrim).

ANALCITE

Analcite.—Hydrated silicate of sodium and aluminium; $Na_2Al_2Si_4O_{12} . 2H_2O$; $Na_2O = 14{\cdot}1$, $Al_2O_3 = 23{\cdot}2$, $SiO_2 = 54{\cdot}5$, $H_2O = 8{\cdot}2$. Cubic; common form, {211}, with {100}. Brittle. Fracture, uneven. $H = 5\frac{1}{2}$; $G = 2{\cdot}2$. Colourless. Streak, white. Lustre, vitreous. Transparent; $\mu = 1{\cdot}487$. Fusible ($2\frac{1}{2}$). Decomposed by hydrochloric acid with gelatinisation.

With the above description compare crystals from the **Cyclopean Islands.**

Analcite only differs in composition from gmelinite by its deficiency in water. Clear glassy icositetrahedra {211}, like Fig. 33, p. 20, are found at several localities, but the crystals are often quite opaque and white or pink in colour, *e.g.* the large white crystals found with quartz, calcite, platy apophyllite and natrolite in amygdaloidal cavities of melaphyre at the Seisser Alp in the Tyrol. Analcite almost always exhibits weak birefringence, and, like leucite, is resolved under the microscope into sectors which do not extinguish together. The crystals must therefore be regarded as pseudo-cubic. These "optical anomalies" will be considered below, with the optical characters of the zeolites as a whole.

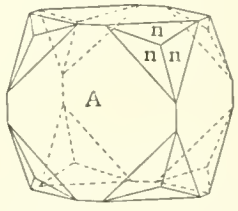

Fig. 630.—Analcite from Cyclopean Islands, A {100}, *n* {211}.

Before the blowpipe analcite fuses to a colourless glass, and the large percentage of sodium is indicated by the yellow colour imparted to the flame.

The name was given in allusion to its weak electrification by friction (ἄναλκις, weak).

A Noteworthy Locality:

Cyclopean Islands (near Sicily).—Beautiful glassy crystals occur in the cavities of basalt; these cavities are generally lined or filled with analcite, which is sometimes so large that one crystal may entirely

fill a cavity. The crystals are a combination of {100} and {211} (Fig. 630), and possess a lustre like that of limpid quartz. The cube faces are usually replaced by vicinal planes of a flat icositetrahedron.

THE NATROLITE GROUP

Natrolite.—Hydrated silicate of sodium and aluminium; $Na_2Al_2Si_3O_{10} \cdot 2H_2O$; $Na_2O = 16{\cdot}32$, $Al_2O_3 = 26{\cdot}86$, $SiO_2 = 47{\cdot}36$, $H_2O = 9{\cdot}46$.

Orthorhombic. $a : b : c = 0{\cdot}978 : 1 : 0{\cdot}354$.

$m = \{110\}$, $o = \{111\}$.

$mm\ (110) : (1\bar{1}0) = 88^\circ\ 45'$, $mo\ (110) : (111) = 63^\circ\ 11'$, $oo = (111) : (\bar{1}11) = 37^\circ\ 38'$,

$oo = (111) : (11\bar{1}) = 36^\circ\ 47'$.

Common form, *mo*. Cleavage *m*, perfect. Brittle. Fracture, uneven. $H = 5\frac{1}{2}$; $G = 2{\cdot}2$. Colourless. Streak, colourless. Lustre, vitreous. Transparent; $\beta = 1{\cdot}479$. Birefringence, positive, strong; $\gamma - \alpha = 0{\cdot}012$. Axial plane (010). Acute bisectrix normal to (001). $2E = 99^\circ$; $\rho < r$. Readily fusible (2). Decomposed by hydrochloric acid with gelatinisation.

With the above description compare crystals from **Puy de Dôme.**

Natrolite is the commonest of the fibrous zeolites; it sometimes occurs in the amygdaloidal cavities of basalt in beautiful tufts of acicular crystals, and it is common as a massive fibrous mineral.

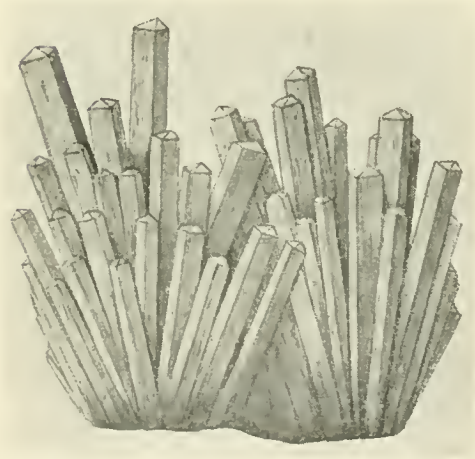

Fig. 631.—Natrolite from Puy de Dôme.

When terminated, the crystals always present the appearance of square prisms terminated by square pyramids (Fig. 631), sometimes with (010) (*cf.* Fig. 632, scolecite). The angles given above indicate that the symmetry is very nearly tetragonal.

Under the microscope it may be recognised by the straight extinction and absence of visible bisectrix or optic axes in a cleavage flake.

It is so fusible that it can be melted in a candle flame, and the colour which it imparts to flame indicates a compound rich in sodium.

A Noteworthy Locality:

Puy Marman (Puy de Dôme, France).—Beautiful white crystals were formerly found here in the cavities of a compact basalt associated with calcite, aragonite, and analcite; these are much larger than the natrolite crystals of most localities. Here, as elsewhere, the prisms are never doubly terminated.

Scolecite.—Among the other acicular or fibrous zeolites the most important is scolecite, a lime zeolite, $CaAl_2Si_3O_{10} \cdot 3H_2O$, corresponding to natrolite in composition, except for the difference of water. It occurs

in crystals having almost exactly the angles of natrolite, but when examined carefully these will be seen to present signs of twinning. They consist, in fact, of two monoclinic crystals, a combination of m {110}, B {010}, o {111}, d {101}, united by twinning and juxtaposition along the plane (100) (Fig. 632).

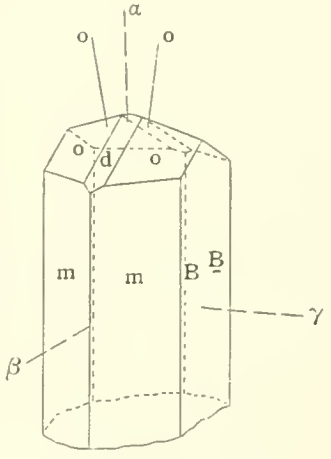

Fig. 632.—Scolecite, B {010}, m {110}, o {111} d {101}, twinned on (100).

Re-entrant angles can generally be seen where the faces (111) of one individual nearly, but not quite, coincide with the faces {111} of the other. Further, the extinction is not straight, as in natrolite, but is inclined at 15° to the vertical in the face B; in such a twin, therefore, the two halves of the plane B extinguish in positions inclined at 30° to each other. The birefringence of scolecite is negative and B is perpendicular to a positive obtuse bisectrix, whereas in natrolite B is perpendicular to the third mean line.

Etching experiments on scolecite and also its pyro-electricity show that this mineral is not holosymmetric but possesses only a plane (without an axis) of symmetry; the back and front prism faces are electrically opposite in character (*cf.* pyroxene); in the twins they are alike.

Scolecite is named from σκώληξ, a worm, in allusion to the manner in which it curls up when fused before the blowpipe (fusibility slightly greater than 2). With acids it behaves like natrolite.

The best crystals of scolecite are the large striated prisms which accompany the pink stilbite on the beautiful specimens from Poonah which have been described on p. 441. It also occurs in fibrous aggregates.

The most finely fibrous mineral of this group is **mesolite**, which, as indicated by its name, is intermediate in composition between natrolite and scolecite. This usually occurs in downy or mealy white masses of minutely acicular crystals, which are very similar to those of scolecite.

Another fibrous or prismatic zeolite which may occur with those already mentioned is the orthorhombic **thomsonite**, also a soda-lime zeolite. This may be recognised under the microscope by the principal {010} cleavage being perpendicular to the positive acute bisectrix ($2E = 90°$), and giving straight extinction with regard to the second cleavage (100).

THE WATER AND OPTICAL PROPERTIES OF THE ZEOLITES

The isomorphism of scolecite with natrolite, and the resemblance of stilbite to heulandite, in spite of their difference in water, indicates that the water of the zeolites is not an altogether essential constituent; much of their water of crystallisation is given up very readily.

A lime zeolite known as laumontite, $CaAl_2Si_4O_{12} \cdot 4H_2O$, loses about

one molecule of its water in dry air at ordinary temperatures, becomes opaque, and crumbles to pieces; a second molecule is removed by heating to 300° C.; the remainder is only given up at a red heat; hence the formula is written $H_4CaAl_2Si_4O_{14} . 2H_2O$, as explained on p. 205.

Similarly, in heulandite about three-fifths of the water is given off at low temperatures, and the formula is regarded as $H_4CaAl_2Si_6O_{18} . 3H_2O$.

With loss of water the zeolites lose their transparency and become dull, but many of them possess the remarkable property of reabsorbing in a moist atmosphere the water which they have lost when heated or exposed to dry air; a heulandite from the Faröe Islands lost 12·3 per cent of water at 190°, and in ordinary air regained 10·1 per cent in two months. Laumontite from Brittany lost 3·85 per cent over sulphuric acid and regained it when exposed to a moist atmosphere.

Still more remarkable is the fact that such zeolites, when they regain their water of crystallisation, regain also their transparency and their original optical properties; this seems to indicate that the crystal edifice is not destroyed when the water is removed, and that the water can re-enter the meshes of the structure.

Not only is twinning very prevalent among the zeolites, as has been shown above, but even apparently simple crystals, or the portions which unite to form an interpenetrant twin, are usually found to be pseudo-symmetric when their optical properties are examined. Heulandite, phillipsite, harmotome, stilbite, chabazite, gmelinite, analcite, all show differently orientated sectors or patches which do not extinguish together when a section is examined between crossed nicols. In the case of chabazite the rhombohedral crystal is sometimes uniaxial, sometimes slightly biaxial, and the birefringence is sometimes positive and sometimes negative. This behaviour, as explained on p. 233, points to an isomorphous intermixture of two substances of different optical characters. Now chabazite varies considerably in composition; accordingly many attempts have been made to explain its constitution as a mixture of two isomorphous compounds. Streng suggested $CaAl_2Si_2O_8 . 4H_2O$ with $CaAl_2Si_6O_{16} . 8H_2O$, two compounds which display an isomorphous relationship somewhat similar to that of the felspars.

Equal difficulties are experienced in the case of the phillipsite group. Groth, for example, represents phillipsite as a mixture of $CaAl_2Si_2O_8 . 3H_2O$ with $CaAl_2Si_6O_{16} . 6H_2O$, and other authors have suggested other formulæ.

The pseudo-symmetry of the zeolites may therefore be due in some instances to the mimetic twinning, not only of two crystals of the same compound, but of two isomorphous compounds.

As in many pseudo-symmetric minerals (*e.g.* boracite and leucite), change of temperature produces marked changes in the optical characters.

Analcite possesses the definite composition $(Na_2, Ca)Al_2(SiO_3)_4 . H_2O$, and gives up its water above 200°; it almost always displays a weak double refraction, and, unlike boracite and leucite, does not become isotropic when heated, but becomes more strongly birefringent. Some authors have for this reason attributed the birefringence to internal

strain; since, however, the crystals are said to become isotropic when warmed in a moist atmosphere, others are disposed to attribute the birefringence to a slight loss of water. However this may be, the loss of water in most zeolites certainly produces well-defined optical changes. It is impossible to distinguish between water of constitution and water of crystallisation. In all these minerals water continues to be gradually driven off as the temperature is raised. Thus in heulandite, Mallard showed that with increase of temperature up to 150° the extinction angle and the angle between the optic axes gradually change as the water is gradually lost, and return to their original values as it is reabsorbed. During heating, the optic axes close in upon the normal of B and then open out in a plane almost at right angles to the original axial plane. At 180° the crystal becomes opaque and permanently altered. Rinne found that by immersing in oil heulandite which has been thus altered, it becomes transparent and possesses the definite optical characters of a crystal; the crystalline structure has, therefore, not been destroyed. At 150°, when two molecules of water have been lost, the negative bisectrix (a) is perpendicular to C (001). At 180°, when three molecules of water have been lost, the positive bisectrix (γ) is perpendicular to s ($20\bar{1}$) (Fig. 628, p. 486). At 150° the symmetry of the structure is orthorhombic. Hence at ordinary temperatures the cleavage B is perpendicular to γ, at 150° to β, and at 180° to a.

Many zeolites thus transformed by heat may be soaked in oil, which prevents reabsorption of the lost water, and makes the optical properties of the dehydrated crystal visible and permanent.

For example, natrolite heated to 250° loses most of its water and becomes dull, but immersed in oil is found to possess the optical characters of a monoclinic crystal with the vertical line for its axis of symmetry.

In heulandite two molecules of water may be removed by the action of sulphuric acid without heating, and the effect is precisely the same as that of heating to 150°.

A still more remarkable feature of the zeolites is that their water may be replaced by other substances, such as ammonia, hydrogen sulphide, ethyl alcohol; the dehydrated crystals absorb definite quantities of these substances as a sponge absorbs water; the process is accompanied by evolution of heat.

It is generally concluded from these observations that the water of the zeolites is not analogous to the water of crystallisation of most hydrated salts, but resembles more nearly the intermixture which takes place in a solid solution.

SECTION XXIII

SILICATES CONTAINING WATER OF CONSTITUTION

THE EPIDOTE GROUP

Epidote.—$HCa_2Al_3Si_3O_{13}$; $CaO = 24{\cdot}6$, $Al_2O_3 = 33{\cdot}9$, $SiO_2 = 39{\cdot}5$, $H_2O = 2{\cdot}0$; containing also Fe_2O_3 (up to 16 per cent), replacing Al_2O_3. Monoclinic.

$$a : b : c = 1{\cdot}579 : 1 : 1{\cdot}804. \quad \beta = 64^\circ\ 37'.$$

$A = \{100\}$, $C = \{001\}$, $e = \{101\}$, $i = \{\bar{1}02\}$, $r = \{\bar{1}01\}$, $l = \{\bar{2}01\}$, $f = \{\bar{3}01\}$, $n = \{\bar{1}11\}$, $o = \{011\}$, $k = \{012\}$, $d = \{111\}$, $z = \{110\}$, $u = \{210\}$, $q = \{221\}$, $y = \{21\bar{1}\}$, $B = \{010\}$.

$AC\ (100) : (001) = 64^\circ\ 37'$, $Ci\ (001) : (\bar{1}02) = 34^\circ\ 21'$, $ir\ (\bar{1}02) : (\bar{1}01) = 29^\circ\ 21'$, $Bo\ (010) : (011) = 31^\circ\ 32'$, $Bn\ (010) : (\bar{1}11) = 35^\circ\ 14'$, $on = (011) : (\bar{1}11) = 33^\circ\ 56'$, $on = (011) : (1\bar{1}\bar{1}) = 56^\circ\ 3'$, $An\ (100) : (11\bar{1}) = 69^\circ\ 2'$.

Twinned on A. Cleavage C, perfect; A, imperfect. Brittle. Fracture, uneven. $H = 6\frac{1}{2}$; $G = 3{\cdot}4$. Dark green. Streak, gray. Lustre, vitreous. Translucent; $\beta = 1{\cdot}757$. Birefringence, strong, negative; $\gamma - a = 0{\cdot}04$. Axial plane, B. Acute bisectrix inclined at 22° 37′ to normal of C, and at 87° 14′ to normal of A; $2H = 91^\circ\ 20'$. Dispersion (inclined), strong, $\rho > v$. Pleochroism, strong. Fusible with difficulty ($3\frac{1}{2}$). Partially decomposed by hydrochloric acid.

With the above description compare crystals from **Sulzbachthal** (Tyrol).

Epidote is a not uncommon rock constituent; the best specimens are found in druses of the crystalline schists, generally in long prisms, and, unlike most monoclinic minerals, elongated along the axis of symmetry. The crystals are sometimes very rich in faces, both in the principal striated zone of the orthodomes [*eir*], and also in the pyramidal termination *o*, *n*, etc. (Fig. 634). They are excellent material for practice in goniometrical measurement and calculation. Twinning is very frequent, and may generally be recognised by a re-entrant angle dividing the terminal faces by a nick or a twin lamina parallel to A (Fig. 635). The crystals are also sometimes twinned parallel to C.

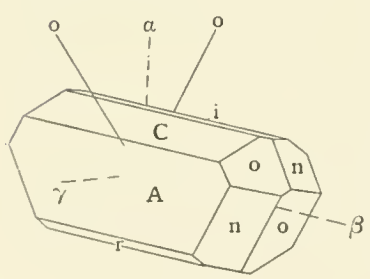

Fig. 633.—Epidote, A {100}, C {001}, *i* {102}, *r* {101}, *o* {011}, *n* {111}.

Ordinary massive epidote is a compact or granular yellowish-green

substance which may be confused with massive pyroxene or idocrase; but the (pistachio green) colour is really somewhat different from that of other minerals. Thin crystals may be pale green; ordinary crystals are nearly black.

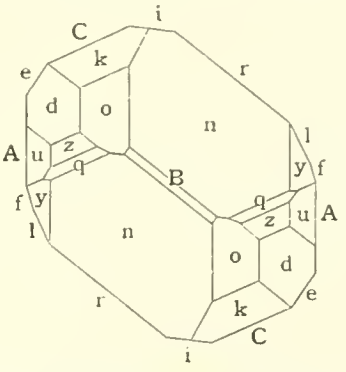

Fig. 634.—Epidote, A {100}, e {101}, C {001}, i {$\bar{1}$02}, r {$\bar{1}$01}, l {$\bar{2}$01} f {301}, k {012}, d {111}, o {011}, n {$\bar{1}$11}, z {110}, q {22$\bar{1}$}, u {210}, y {21$\bar{1}$}.

Under the microscope epidote may be recognised by the strong pleochroism (β brown, α and γ yellow to green), and the visibility of the optic axes as a prism is turned round; the obtuse bisectrix is nearly perpendicular to A. The interference figure is generally complicated by the twinning. Crystals of epidote which are transparent possess a very remarkable property, due to the strong absorption; when viewed through r in the direction of an optic axis they exhibit the so-called "absorption brushes," a pair of dark brushes surrounding a light spot. These are due to the fact that for rays nearly coincident with the optic axis the direction of vibration of the light, and therefore also the absorption, varies very greatly. A similar effect is produced by other crystals possessing very marked absorption, such as andalusite and magnesium platino-cyanide.

The darkest varieties of epidote, which also contain most iron, fuse most easily, and yield a magnetic slag. The faces A and C of Figs. 633, 634, are by most authors called T and M (C is denoted by M in Fig. 635), and sometimes receive the indices ($\bar{1}$01) and (100) respectively.

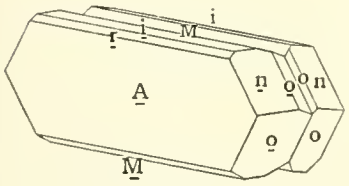

Fig. 635.—Epidote twinned on (100).

A Noteworthy Locality:

Knappenwand (Untersulzbachthal, Tyrol).—Magnificent dark green crystals with the faces of Figs. 633 and 634 occur on massive or fibrous epidote in cavities of an epidote schist. The associated minerals are white adularia, glassy apatite, and finely fibrous or hair-like green asbestos, also drusy calcite and titanite. The crystals are mostly twinned; B is quite small and sometimes rough.

Zoisite is the name given to an orthorhombic mineral having nearly the same composition as epidote; at the Ducktown Copper Mines in Tennessee it is found in gray prisms with chalcopyrite, quartz, pyrites, and blende; the acute positive bisectrix ($2E = 50^\circ$) emerges through (100), but the axial plane is sometimes parallel to (010), sometimes to (001).

Some of the angles of zoisite are nearly equal to some of epidote, and there is evidently a close relationship between the two minerals; zoisite, however, contains very little iron, and therefore approximates most closely to the formula given above for epidote.

A beautiful massive red mineral, known as "thulite," which occurs with blue idocrase, garnet, epidote, and fluor in Telemark in Norway, and is used as an ornamental stone, is referred to zoisite. The colour is due to manganese.

VESUVIANITE

Vesuvianite.—Silicate of aluminium and calcium (with MgO, Fe_2O_3, and H_2O). Tetragonal (or pseudo-tetragonal); symmetry, holosymmetric.

$$a : c = 1 : 0{\cdot}5375.$$

C {001}, *m* {110}, A {100}, *p* {111}, *s* {311}.

pp (111) : (1$\bar{1}$1) = 50° 40′, C*p* (001) : (111) = 37° 14′, A*s* (100) : (311) = 35° 9′, *ss* (311) : (13$\bar{1}$) = 45° 21′.

Cleavage A, *m*, imperfect. Brittle. Fracture, conchoidal. H = 6½; G = 3·41. Colour, green. Streak, white. Lustre, vitreous. $\omega = 1{\cdot}722$. Double refraction, weak, negative; $\omega - \epsilon = 0{\cdot}001$. Pleochroic. Fusible (3) to a coloured glass. Scarcely affected by acids.

With the above description compare crystals from **Ala** (Piedmont).

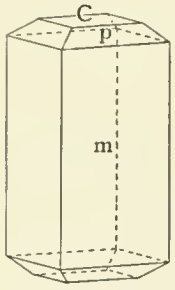

Fig. 636.—Vesuvianite, *m* {110}, *p* {111}, C {001}.

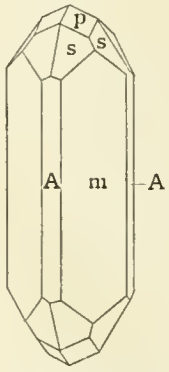

Fig. 637.—Vesuvianite, A {100}, *m* {110}, *p* {111}, *s* {311}, from Ala.

Vesuvianite (or idocrase) is generally found in brown crystals (as at Christiansand in Norway), like Fig. 636. The above description relates to the small green crystals (Fig. 637) found in the Alathal, which are the best crystallised and the most transparent. The prism faces of vesuvianite are vertically striated, and the basal plane is sometimes tesselated. The name is derived from the locality, Mount Vesuvius, where finely crystallised brilliant brown crystals are found. Here, as elsewhere, the vesuvianite may be distinguished from other minerals (garnet, etc.) which it may resemble, by a striated prism zone perpendicular to a smooth basal plane. Twinning is unknown. Vesuvianite is one of the best examples of tetragonal crystallisation; it is mostly found in metamorphic limestone and crystalline schists, and as a contact mineral.

Considerable variations in the angles, in the colour, in the optical properties, and in the composition, indicate that it may be an isomorphous mixture of two or more undetermined silicates. The crystals

are often slightly biaxial; the birefringence of those from the river Wilui in Siberia is positive; there is often a division into sectors, to be observed in polarised light, and still more usual is a zonal growth of differently coloured material, or of bands which do not extinguish together. The axial angle in the biaxial zones may rise to 60°. The large prisms from the Wilui consist of wedges of two materials arranged hour-glass fashion; the two wedges which have the basal pinakoid for their bases are nearly uniaxial; those which extend laterally to the prism faces consist of lamellæ having an axial angle of about 30°. Basal sections of vesuvianite generally have a quadrangular zonal structure. The mineral is probably to be regarded as pseudo-tetragonal, and composed of monoclinic sub-individuals. The dichroism is not very pronounced.

Most vesuvianite has approximately the following composition:— $SiO_2 = 37$ to 39; $Al_2O_3 = 13$ to 16; $CaO = 33$ to 37; $Fe_2O_3 = 0$ to 6; $MgO = 1$ to 4; $H_2O = 0$ to 3.

In composition, vesuvianite is very near to the lime alumina garnet, $Ca_3Al_2Si_3O_{12}$, containing in addition a little water (2 to 3 per cent), which is given off at a red heat, and also frequently magnesium and alkalies; some analyses of vesuvianite have led to the formula $H_4Ca_{12}Al_6Si_{10}O_{43}$. Rammelsberg regards the mineral as $R'_{22}Si_5O_{21}$, where R′ may be H or equivalent quantities of Ca, Mg, Al, Fe.

Some Noteworthy Localities:

Ala (Piedmont).—Here, in the place which yields the well-known specimens of garnet and diopside (p. 422), is found idocrase of three sorts: (1) beautiful green prisms rich in terminal faces, accompanied by chlorite, upon massive vesuvianite which traverses serpentine; (2) acute pyramidal, green, or brownish crystals (Fig. 637), accompanied by diopside and chlorite (with apatite) upon garnet, both crystallised and massive, which also traverses the serpentine; (3) long thin striated prisms of a reddish-brown colour (wrongly called manganese idocrase), accompanied by garnet, diopside, and chlorite upon garnet.

Monzoni (Tyrol).—Here, adjoining the Fassathal, in a bluish granular limestone, together with massive spinel and augite, are found yellow and greenish crystals of considerable size, of a pyramidal habit, form *p*. The vesuvianite is drusy and partly altered into steatite.

Vesuvius.—In the druses of the ejected limestone blocks of **Monte Somma** are found brilliant prisms of brown vesuvianite accompanied by garnet, both brown and yellow, green plates of meroxene, hornblende, sanidine, wollastonite, nepheline, etc. The vesuvianite is sometimes tabular, owing to the predominance of C {001}.

Christiansand (Norway).—Large brown crystals in calcite in the gneiss, associated with garnet. These are prisms with large basal plane and small pyramid faces, and show a zonal structure.

Achmatovsk (Urals).—Green and brown crystals in the chlorite schist, or in calcite enclosed in the schist. Most of these are prismatic, but some of the little green crystals are low pyramids without prism

faces terminated by small faces of the basal pinakoid, and of a habit so unusual for vesuvianite that they were formerly mistaken for sphene.

River Wilui (Siberia).—Large greenish-brown square prisms of the usual habit, known as "wiluite," occur in a tufaceous decomposed rock with green garnet and peculiar tetrahedral pseudomorphs known as "achtaragdite." The vesuvianite exhibits a remarkable tesselation on its faces.

PREHNITE

Prehnite, $H_2Ca_2Al_2Si_3O_{12}$, is an orthorhombic mineral which occurs under the same conditions as the zeolites, and is often associated with them; since, however, it only loses its water at a red heat, it can scarcely be classified with the zeolites.

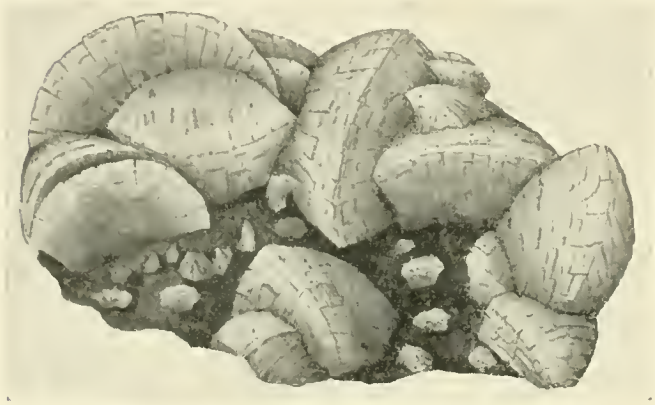

Fig. 638.—Prehnite from Bourg d'Oisans (British Museum).

Definite crystals are very rare, and the mineral has an extraordinary tendency to appear in barrel-shaped or globular groups, as shown in Fig. 638, which can be seen, if carefully examined, to consist of rectangular plates; it is translucent, and of a pale green or gray colour. Distinct crystals somewhat resemble hemimorphite, and, like that mineral, are pyro-electric and therefore polar, but the polarity may be concealed by supplementary twinning (p. 90). The optical properties suggest that the prehnite is pseudo-rhombic. Prehnite is fusible (2) with intumescence to an enamel, and is decomposed by hydrochloric acid. Fine groups have been found at Bourg d'Oisans in Dauphiné (Fig. 638), associated with axinite, and accompanied by epidote, orthoclase, albite, and calcite, and sometimes enveloped by white asbestos.

AXINITE

Axinite, of which beautiful specimens occur at Bourg d'Oisans with the prehnite, is interesting crystallographically as a finely developed anorthic mineral, and chemically as a borosilicate (like tourmaline). The name, like that of sphene, refers to the wedge shape of the crystals (ἀξίνη, an axe). The crystals are clove-brown in colour, transparent and brilliant, possessing a vitreous, almost adamantine, lustre; the zones M*m* and M*x* are striated parallel to their edges; H = 6½; G = 3·28; M = 110,

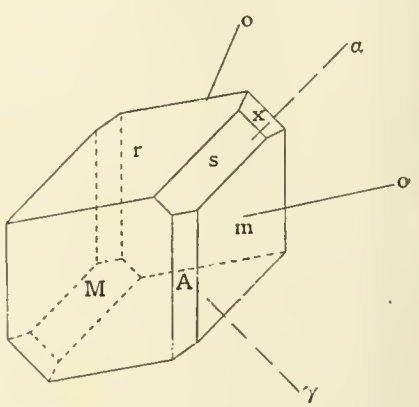

Fig. 639.—Axinite, A {100}, M {1$\bar{1}$0}, *m* {110}, *s* {201}, *x* {111}, *r* {1$\bar{1}$1}.

$m = \{110\}$, $A = \{100\}$, $r = \{\bar{1}11\}$, $s = \{201\}$, $x = \{111\}$. It is strongly pleochroic, optically negative with strong birefringence, a large axial angle ($2H = 85°$) (Fig. 639), and very marked dispersion, $\rho < r$.

Composition approximately $HCa_3Al_2BSi_4O_{16}$, where Ca is partly replaced by Fe and Mn.

Axinite fuses readily (at 2) with intumescence, and is not decomposed by acids. The presence of boron can be detected as in tourmaline.

Crystals very similar to those of Dauphiné occur in the cliffs at Botallack, near St. Just, Cornwall.

STAUROLITE

Staurolite has been mentioned above (p. 88) as one of the most striking examples of cruciform interpenetration twinning, and to this its name alludes (*σταυρός*, a cross); it is an orthorhombic aluminium silicate resembling andalusite in composition, but contains about 16 per cent of FeO and MgO, and less than 2 per cent of water, which is retained at a high temperature; the crystals are usually so impure that the formula has not been established with certainty, but some analyses lead nearly to $HFeAl_5Si_2O_{13}$; they are often partially altered to a steatitic substance, and contain silica and other minerals. Sharply-crystallised brown prisms—simple crystals like one arm of Fig. 640—occur in the white paragonite-schist of Monte Campione (St. Gothard), associated with cyanite and garnet, and, as mentioned on p. 86, these are sometimes

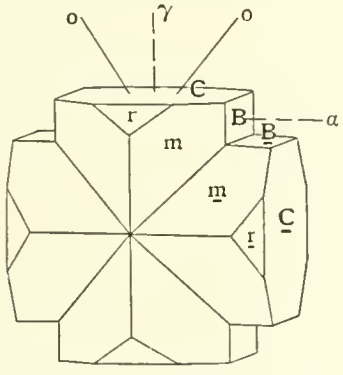

Fig. 640.—Staurolite, B {010}, *m* {110}, C {001}, *r* {101}, twinned on (032).

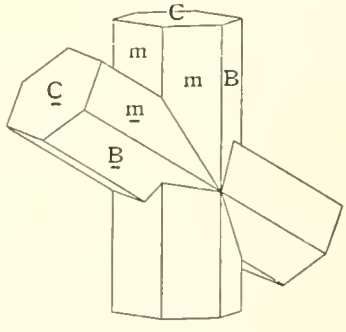

Fig. 641.—Staurolite twinned on (232).

united in regular position with cyanite (Fig. 21); it is upon these crystals that the form and optical properties of the mineral may best be determined; $mm = (110) : (1\bar{1}0) = 50° 40'$; $Cr = (001) : (101) = 55° 16'$; hence $a : b : c = 0{\cdot}473 : 1 : 0{\cdot}683$; positive acute bisectrix perpendicular to C; axial plane (100); $2H = 113°$; $\beta = 1{\cdot}75$; birefringence, strong = 0·012; pleochroism very distinct; γ red, α and β yellow to green; but the colours seem to vary in different specimens. It is in the mica schist of Brittany, at Quimper and other localities, that the well-known large twins (Figs. 640 and 641) are found; these are rough brownish crystals containing much quartz. In Fig. 640 the twin plane is (032), and the arms of the cross are inclined to each other at 91° 10′; in Fig.

641 the twin plane is (232), and the arms are inclined at 59° 34′; it is curious that neither the form {032} nor {232} is found as crystal faces. Similar twins in loose isolated crystals are found in a decomposed mica schist in Fannin County, Georgia, and here interpenetration twins on (130) are also not uncommon.

In Brazil, in the diamond washings of Salobro, fragments of staurolite are found sufficiently clear to serve as gemstones; when these are suitably cut, the pleochroism, green to red-brown, is a very striking feature visible in ordinary light.

THE CHLORITE GROUP

Chlorite Group.—Silicates of magnesia (or iron) and alumina, containing also about 12 per cent water, which is given off at a high temperature.

Monoclinic (pseudo-hexagonal). The crystals are hexagonal plates having their edges bevelled by faces inclined at an angle of 66° 17′, or 66° 32′, to the base. These are the angles observed on clinochlore (see p. 499).

The minerals are generally aggregates of small scales, and are mostly decomposition products.

Cleavage, basal, perfect. Flexible. Dark green. Streak, white. Lustre, vitreous, pearly on (001). H = 2 – 3; G = 2·6 – 3·0. $\beta = 1{\cdot}6$. $\gamma - \alpha = 0{\cdot}01$. Different varieties may be uniaxial, biaxial, positive or negative. Pleochroic. Fusible with difficulty. Decomposed by sulphuric acid.

Chlorite.—The minerals comprised in this group are all silicates of alumina and magnesia, and contain water, which is only given off at a red heat; they are sometimes known as the "hydro-micas." In crystalline form they are very similar to the micas, occurring in hexagonal scales, which have a good basal cleavage. The chlorites are distinguished from the micas in being pliable and not elastic; their cleavage, moreover, is not so easy as that of the micas, and they are not so hard. Generally speaking, a soft pliable mineral which occurs in scaly aggregates, and is usually of a greenish colour, is to be referred to the chlorite group, but the name includes a large number of varieties, which are not all well defined. They are, however, easily distinguished from the other minerals of scaly structure, such as mica and talc, since they contain a considerable amount of water; they do not contain any large proportion of alkalies like the former, and the alumina, which is an essential constituent of all chlorites, distinguishes them from talc. They resemble those minerals, however, in being monoclinic and pseudo-hexagonal; the refractive index is near that of talc and mica, but the weaker double refraction serves to distinguish chlorite from either; thin sections usually show no interference rings.

Two well-crystallised varieties are conspicuous among the specimens commonly to be found in collections, namely, pennine and clinochlore.

Pennine occurs in large dark green crystals at Zermatt, accompanied by a fibrous diopside in massive asbestos schist, or "mountain leather"; these crystals are apparently long acute rhombohedra with rough faces terminated by the basal plane, to which they are inclined at an angle of

about 76°. The cleavage flakes are sometimes negative, sometimes positive, and may be either uniaxial or biaxial, but generally the former. Pennine possesses a very remarkable pleochroism; the colour of a section transverse to the cleavage is clear green when viewed by light vibrating parallel to the cleavage trace; yellow-brown or almost red when the light vibrates perpendicular to the cleavage.

Clinochlore occurs in green plates and in curved foliated sheaves in the cavities of a chlorite schist at Achmatovsk in the Urals, where it accompanies beautifully crystallised garnet, diopside, and apatite. The hexagonal tables are bevelled by faces inclined at $71\frac{1}{2}°$ or 66° to the basal plane; they are optically positive, and either uniaxial or biaxial with a small angle; the pleochroism is similar to that of pennine. The acute bisectrix is perceptibly inclined to the cleavage, so that, as indicated by its name, the mineral is distinctly monoclinic.

The occurrence at Achmatovsk is very similar to that at Ala, (Turin), where beautiful little green hexagonal plates accompany the essonite and diopside described on p. 422.

Two very striking chrome-chlorites of a deep rose-red colour from the Urals are known, and have received the names kämmererite and kotschubeite; the first, being nearly uniaxial, has generally been regarded as a variety of pennine.

Three varieties of the chlorite group are generally distinguished—

Pennine, the magnesia chlorite, with about 35 per cent SiO_2.

Clinochlore, the intermediate chlorite, with about 30 per cent SiO_2.

Ripidolite, the iron chlorite, with about 25 per cent SiO_2.

The name chlorite was given by von Kobell of Munich to the mineral from Zillerthal and Salzburg, while the more siliceous mineral from Achmatovsk received the name **ripidolite** on account of its structure (ῥιπίς, fan). The name ripidolite was unfortunately transferred to the sheaf-like groups from St. Gothard, a mineral which contains about 32 per cent of SiO_2, and this has led to considerable confusion in the nomenclature; Dana has suggested the name prochlorite for the chlorite of Kobell.

Until recently the chlorites were divided into three or more classes according to their optical characters, which were supposed to distinguish them into rhombohedral or monoclinic crystals; a chemical classification was not possible. There can now be little doubt that all the minerals of this group belong to the monoclinic system, and that those which are apparently rhombohedral owe their form and their optical characters to the superposition of numerous twin lamellæ, either of the same or of different minerals.

When biaxial crystals, positive and negative, are interlaminated they may give rise to a compound crystal which is apparently uniaxial, and this may be the case with some of the apparently rhombohedral chlorites (cf. the remarks on p. 233).

Now their extremely variable composition shows that the minerals of this group are doubtless mixtures of two or more distinct substances; it was shown by Kenngott that in all the analyses of chlorite, if the

Al_2O_3 be replaced by a corresponding amount of the pyroxene silicate $MgSiO_3$, the composition is reduced to that of serpentine, and may be represented by the formula $H_4Mg_3Si_2O_9$. Consequently, Tschermak regards the chlorites as isomorphous mixtures in varying proportions of the two molecules—

(Serpentine), $H_4Mg_3Si_2O_9$.
(Amesite), $H_4Mg_2Al_2SiO_9$.

The latter corresponds nearly to a chloritic mineral from Chester (Massachusetts), known as "amesite."

If this theory of the chlorite group be confirmed, the group MgSi must be considered capable of replacing the group Al_2.

For the more massive and minutely crystalline varieties (which Tschermak has classed together as "leptochlorites"), a more complicated composition must be assumed.

Chlorite occurs in large quantities as chlorite schist, of which it is an essential and almost the only constituent; this is, for example, the matrix of the crystallised clinochlore at Achmatovsk. Otherwise, the chlorites are generally decomposition products of mica, garnet, pyroxene, amphibole, and felspar, as an earthy substance filling cavities in schists and altered eruptive rocks of all sorts. Vesicular cavities in basaltic rocks are frequently filled with fine scaly chlorite. Many of the altered micas have received the name "vermiculite" owing to the manner in which they swell and curl before the blowpipe flame.

Another group of micaceous minerals is known as the **clintonite group**, or the "brittle micas"; they are more brittle than mica, which they closely resemble, being also monoclinic but pseudo-hexagonal with perfect basal cleavage; they are harder than the chlorites (H = 6), and contain much less water. The most interesting mineral of this group is **margarite**, which has already been mentioned as a lime mica. Margarite occurs in white scales of pearly lustre; the name is derived from *μαργαρίτης*, a pearl; H = 4, G = 3. Acute bisectrix nearly perpendicular to the cleavage; $2E = 120°$ about. The composition of this mineral appears to be quite definite, $H_2CaAl_4Si_2O_{12}$. Margarite is a very frequent associate of corundum, as at the emery mines of Asia Minor and of Massachusetts; margarite and diaspore are the common alteration products of corundum.

SECTION XXIV

SILICATES (*Continued*)

BERYL

Beryl.—Silicate of beryllium and aluminium; $Be_3Al_2Si_6O_{18}$; BeO = 14·11, Al_2O_3 = 19·05; SiO_2 = 66·84. Hexagonal; holosymmetric.

$$a : c = 1 : 0{\cdot}4989.$$

$m = \{10\bar{1}0\}$, $p = \{10\bar{1}1\}$, $u = \{20\bar{2}1\}$, $s = \{11\bar{2}1\}$, $v = \{21\bar{3}1\}$, $C = \{0001\}$. Cp $(0001) : (10\bar{1}1) = 29^\circ\ 56'$, Cu $(0001) : (20\bar{2}1) = 49^\circ\ 2'$, Cs $(0001) : (11\bar{2}1) = 44^\circ\ 56'$, pp $(10\bar{1}1) : (01\bar{1}1) = 28^\circ\ 54'$, uu $(20\bar{2}1) : (02\bar{2}1) = 44^\circ\ 22'$, vv $(21\bar{3}1) : (12\bar{3}1) = 18^\circ\ 11'$, mv $(10\bar{1}0) : (21\bar{3}1) = 37^\circ\ 49'$, ms $(10\bar{1}0) : (11\bar{2}1) = 52^\circ\ 17'$.

Cleavage C, imperfect. Brittle. Fracture, conchoidal. H = $7\frac{1}{2}$; G = 2·7. Bluish-green. Streak, white. Lustre, vitreous. Transparent; $\omega = 1{\cdot}584$. Birefringence, negative, weak; $\omega - \epsilon = 0{\cdot}006$. Fusible with difficulty ($5\frac{1}{2}$). Insoluble in acids.

With the above description compare crystals from **Ekaterinburg** (Urals).

Beryl in its pale green varieties, known as aquamarine, and the dark green varieties, known as emerald, is familiar as a precious stone; fine specimens of beryl are found in the pegmatitic veins of some granites, while emerald has been found in slate and limestone in Colombia, and in schist at Takowaya in the Urals, which has been mentioned as the locality of alexandrite.

Beryl is among minerals the best, and almost the sole example of holosymmetric hexagonal symmetry.

Beautiful little pale green crystals from Nerchinsk present excellent material for measurement; they are very bright and rich in faces and zones. Fig. 642 represents a common combination, but here and at other localities the crystals are sometimes a simple combination of prism and basal pinakoid, with perhaps one pyramid form, such as p or s. The prism faces are almost always striated vertically.

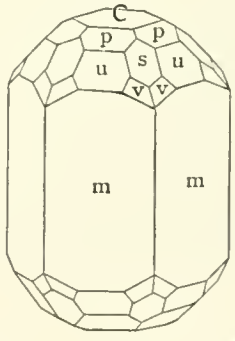

Fig. 642.—Beryl. m $\{10\bar{1}0\}$, p $\{10\bar{1}1\}$, u $\{20\bar{2}1\}$, s $\{11\bar{2}1\}$, v $\{21\bar{3}1\}$, C $\{0001\}$. (Compare Fig. 164.)

Although the angles betray no deviation from hexagonal symmetry, and twinning is unknown, yet the crystals are frequently biaxial in parts; this may be due to strain.

The ordinary beryl found in pegmatite is generally in striated prisms without terminations; massive beryl may resemble apatite; it has, for example, been several times described as occurring in the augite syenite of South Norway, but on nearer investigation the mineral has always proved to be apatite. Beryl can be distinguished from apatite by its superior hardness and inferior cleavage.

The rich green colour of the emerald is almost certainly due to traces of chromium; in hardness and refractive power it is inferior to most gemstones; the specific gravity and refractive index are such as to render the variously coloured aquamarines and emeralds easy of determination by means of methylene iodide and the total reflectometer. Flawless crystals of emerald are extremely rare.

Some Noteworthy Localities:

Ekaterinburg (Urals).—At **Mursinka** and other localities in this district, in druses of the coarse granite, with topaz and black tourmaline, are found beautiful crystals of green, blue, or yellow colour, either a simple combination of C*m*, or C*m* with *p* and *s*, or complex combinations like Fig. 642.

Nerchinsk (Transbaikal).—Very similar crystals, only more striated, are found with topaz and smoky quartz in the granite. At both

Fig. 643.—Beryl with Topaz from Adunchilon (British Museum).

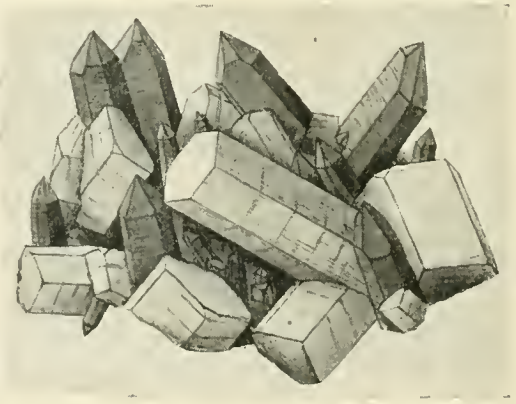

Fig. 644.—Beryl with Smoky Quartz and Orthoclase from the Mourne Mountains.

localities are sometimes found drusy crystals deeply etched and rounded into pyramidal terminations. Neither natural nor artificial etching, however, has indicated anything less than holosymmetry in the mineral.

Fig. 643 represents a striated prism of ordinary beryl associated with topaz from **Adun-chilon** in this district.

Elba.—In druses of the tourmaline granite of **San Piero** (p. 481)

are found richly terminated beryls with predominant basal pinakoid, colourless or tinted either red, green, or blue.

Mourne Mountains (County Down, Ireland).—Fine blue prisms, C*m*, are found in druses of the albitic granite with orthoclase, topaz, and smoky quartz (Fig. 644); these have generally a zigzag zonal structure, indicative of pyramid faces, near the end.

Muso (Colombia).—From this locality have been brought since the sixteenth century the beautiful deep green emeralds of the jewellers' trade. They occur as prisms (C*m*, etc.) in a black bituminous limestone which contains ammonites, and are accompanied by white calcite, clear rock-crystal and black dolomite, together with crystals {210} of iron pyrites. A rare carbonate of lanthanum, known as parisite, is also found here in brown hexagonal pyramids. The emerald crystals are often fractured and recemented by calcite.

The names beryl (*βήρυλλος*) and emerald (*σμάραγδος*) are ancient names of unknown signification.

THE GARNET GROUP

Garnet.—$R''_3R'''_2(SiO_4)_3$, where $R'' = Ca, Mg, Fe, Mn$; $R''' = Al, Fe, Cr$. Cubic. $H = 7$; $G = 3{\cdot}8$. Honey-yellow. Streak, white. Common form, dodecahedron. Cleavage {110}, imperfect. Brittle. Fracture, uneven. Lustre, vitreous to greasy. Transparent; $\mu = 1{\cdot}7 - 1{\cdot}8$.

With the above description compare andradite from **Ala** (Turin).

The following varieties of garnet are distinguished :—

Grossular, $Ca_3Al_2(SiO_4)_3$; $G = 3{\cdot}5$; $H < 7$; fusible (3).
Pyrope, $Mg_3Al_2(SiO_4)_3$; $G = 3{\cdot}7$; $H > 7$; fusible (> 3).
Spessartite, $Mn_3Al_2(SiO_4)_3$; $G = 3{\cdot}8$; $H > 7$; fusible (3).
Almandine, $Fe_3Al_2(SiO_4)_3$; $G = 3{\cdot}5 - 4{\cdot}3$; $H > 7$; fusible (3).
Uvarovite, $Ca_3Cr_2(SiO_4)_3$; $G = 3{\cdot}4$; $H = 7$; infusible (6); green.
Andradite, $Ca_3Fe_2(SiO_4)_3$; $G = 3{\cdot}8 - 4{\cdot}1$; $H < 7$; fusible (3).

All the garnets are isomorphous mixtures of the above, so that colour and composition are very variable. All except uvarovite are decomposed with difficulty by hydrochloric acid, andradite the most easily; ferriferous garnets fuse to a magnetic globule.

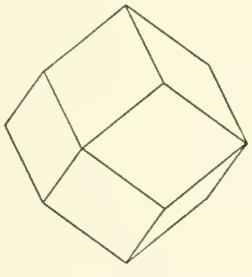

Fig. 645.—Garnet, {110}.

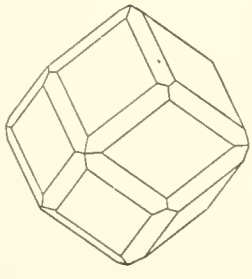

Fig. 646.—Garnet, {110}, {211}.

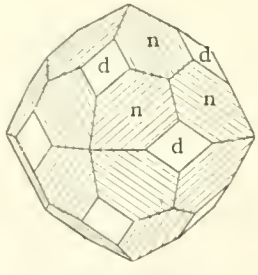

Fig. 647.—Garnet, *n* {211}. *d* {110}.

Garnet (*Germ.* Granat, *Fr.* Grenat).—The garnet group includes an extremely well-defined series of minerals, comprised under the above general formula $R''_3R'''_2(SiO_4)_3$, and recognised by the dodecahedral

or icositetrahedral form, strong refraction, somewhat greasy lustre, imperfect cleavage, and ready fusibility.

Garnet occurs most commonly in the crystalline schists, gneisses, and granulites, or as a constituent (grossular) of lime-silicate hornfels; also as an occasional accessory constituent (andradite) of the alkaline basic rocks, such as phonolite and leucitophyre. In these rocks the garnet usually occurs in grains. In microscopic sections it is recognised by its square or hexagonal outline, strong refraction, absence of cleavage, and isotropic or nearly isotropic character.

One remarkable rock of which garnet is an essential and important constituent is eclogite, a schistose rock consisting of green hornblende ("smaragdite"), green augite ("omphacite") and garnet; this rock occurs at the Sau-alpe in Carinthia.

Garnet sometimes occurs in such large masses, associated with hornblende and magnetite, among the crystalline schists as to constitute a garnet rock. It is also found (pyrope and demantoid) in serpentines and peridotites, and (almandine and spessartite) in granite.

Generally speaking, the lime-alumina garnets are found as secondary minerals in metamorphic rocks (especially limestones); the iron-alumina garnets in granitic and gneissic rocks; the manganese-alumina garnets in granitic rocks; the magnesia garnets in basic rocks containing magnesia; while the lime-iron garnets are of widespread occurrence.

The finely crystallised specimens of museums come mostly from crystalline schists or from metamorphic limestones.

The garnet group is essentially dodecahedral in habit; all the common crystals of garnet are either simple dodecahedra (Fig. 645) or dodecahedra d with their edges truncated by the icositetrahedron n {211} (Figs. 646, 647, 649). In these the faces of n are striated parallel to their intersections with d. Sometimes the dodecahedron edges are also bevelled by {321}, whose faces replace the edges nd of Fig. 647.

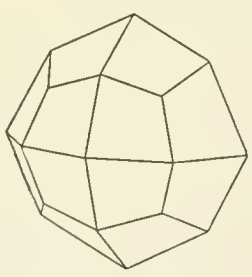

Fig. 648.—Garnet, {211}.

The simple icositetrahedron {211} is a characteristic form of the crystals from the River Wilui and from some other localities (Fig. 648).

Although the mineral is almost invariably dodecahedral, other forms are of course possible; simple white or yellow *octahedra* have been found in Elba; but, as a rule, the only faces of importance are such as belong to the dodecahedral zones. Twinning is unknown.

Optically, very few garnets are quite isotropic, but many, especially the rock-forming crystals, are very nearly so; on the other hand, some garnets are obviously pseudo-cubic, and consist of interpenetrating subindividuals; these are sometimes uniaxial and sometimes biaxial. Klein has referred the structure of garnet crystals to four types: (1) octahedral, in which four uniaxial individuals interpenetrate with their bases in the octahedron faces; (2) dodecahedral, in which six biaxial individuals have each an acute bisectrix perpendicular to a dodecahedron face and the optic axial plane parallel to a longer diagonal; (3) icositetrahedral, in

which twelve uniaxial or biaxial individuals have each an axis or acute bisectrix perpendicular to an icositetrahedron face; (4) topazolitic, in which twenty-four biaxial individuals interpenetrate.

As a result of these observations some authors regard the optical anomalies of garnet as dependent merely on the external form of the crystals, and therefore not the result of pseudo-symmetry; on the other hand, they may indicate that the minerals of the garnet group are mixtures of two or more pseudo-cubic substances, which may be uniaxial or biaxial, together with one or more isotropic substances.

Grossular, lime-alumina garnet (from *grossularia*, a gooseberry, in allusion to the green colour of some varieties).

$SiO_2 = 40{\cdot}01$, $Al_2O_3 = 22{\cdot}69$, $CaO = 37{\cdot}30$, generally containing also iron, manganese, and magnesium in small quantities.

Some Noteworthy Localities:

Ala (Turin).—In the cavities of a massive red grossular traversing serpentine at the head of the Alathal. This valley lies in the zone of schists, serpentines, and gabbros which surround the granitic gneiss of the Graian Alps.

The garnet (so-called essonite or cinnamon-stone) occurs in brilliant hyacinthine-red dodecahedra with {211} {321}, associated with crystals of green diopside, vesuvianite, and chlorite, forming one of the most beautiful mineral associations to be found in collections (see p. 422).

Monzoni (Tyrol).—In veins at the contact of crystalline limestone with augite-syenite; green and yellow icositetrahedra {211}, sometimes with vesuvianite and calcite (see p. 495).

Vesuvius.—In the ejected blocks of **Monte Somma** lustrous yellow or brown crystals {110}, or {110} with {211}, with idocrase, wollastonite and green meroxene (see p. 477).

Jordansmühl (Silesia).—*Colourless* glassy dodecahedra on massive prehnite in serpentine.

Achtaragda River (Siberia). Green *icositetrahedra* with vesuvianite and "achtaragdite" in a volcanic tuff (see p. 496).

Cziklova (Hungary).—Brown and yellow dodecahedra, sometimes with *cube* faces.

Telemark (Norway).—*White* greasy dodecahedra with blue vesuvianite (cyprine), thulite, fluor and quartz; these garnets contain manganese.

Pyrope (Böhmischer Granat).—Magnesia-alumina garnet (from πυρωπός, fiery-eyed).

$SiO_2 = 44{\cdot}78$, $Al_2O_3 = 25{\cdot}40$, $MgO = 29{\cdot}82$, containing also iron and calcium. Blood-red; fusible with difficulty. This is the mineral which supplies the common red garnet of jewellery.

Some Noteworthy Localities:

Meronitz (Bilin, Bohemia).—Angular grains in a conglomerate of marl, serpentine, granulite, gneiss, etc. The pyrope is enclosed in the serpentine, which is itself an alteration product of olivine, and it may

therefore have been originally a constituent of a rock of the nature of eulysite. Some of the grains have the form of rough *cubes*.

South Africa.—Red angular grains accompanying the diamond in the serpentinous conglomerate known as "blue ground," and found also in the river washings; these are also sometimes of cubic habit.

Spessartite, manganese-alumina garnet.

$SiO_2 = 36{\cdot}30$, $Al_2O_3 = 20{\cdot}75$, $MnO = 42{\cdot}95$, always containing also much iron (FeO).

Some Noteworthy Localities:

Aschaffenburg (Spessart in Bavaria).—Yellow to red icositetrahedra in granite.

Haddam (Connecticut).—Large red masses in granite.

Belgium.—In granules in the hone-stones of the Ardennes, and in a black metamorphic quartzite from **Bastogne.**

Nathrop (Colorado).—Bright isolated reddish-brown icositetrahedra occur with topaz in the cavities or lithophyses of a banded rhyolite.

Almandine (precious garnet), iron-alumina garnet (the name is a corruption of Pliny's *alabandicus*).

$SiO_2 = 36{\cdot}15$, $Al_2O_3 = 20{\cdot}51$, $FeO = 43{\cdot}34$, generally contains also calcium, magnesium, and manganese.

Some Noteworthy Localities:

St. Gothard (Switzerland).—Red and brown dodecahedra and icositetrahedra in mica-schist and gneiss.

Fig. 649.—Almandine on Mica Schist from Alaska.

Fahlun (Sweden).—Red dodecahedra, in chlorite, associated with iron and copper ores.

Ceylon and **India.**—Nodules used for jewellery. When cut *en cabochon* these are known as "carbuncles."

Botallack (St. Just, Cornwall).—Red icositetrahedra in the hornblende schist of the cliffs.

Fort Wrangell (Alaska).—Beautiful red dodecahedra truncated by {211} occur here in a mica schist (Fig. 649); these crystals are remarkably symmetrical.

Almandine generally has a somewhat characteristic purplish-red colour; it is used considerably in jewellery, often cut *en cabochon* with a rounded surface. Under the microscope almandine is usually seen to contain very fine hair-like fibres of some mineral, and it always yields, when viewed with a spectroscope, the characteristic absorption spectrum of Fig. 416, p. 276.

Uvarovite, lime-chrome garnet (named after a Russian minister).

$SiO_2 = 38{\cdot}23$, $Cr_2O_3 = 32{\cdot}50$, $CaO = 29{\cdot}27$, containing also aluminium and iron. Green; infusible.

Some Noteworthy Localities:

Bisersk (North Urals).—Small, brilliant, emerald-green dodecahedra in cavities in chromite.

Orford (Canada).—Small dodecahedra in granular limestone with pyroxene.

Andradite (common garnet), lime-iron garnet (named after a Portuguese mineralogist).

$SiO_2 = 35{\cdot}45$, $Fe_2O_3 = 31{\cdot}49$, $CaO = 33{\cdot}06$, generally containing also aluminium and magnesium; the black variety (melanite) contains titanium.

Some Noteworthy Localities:

Ala (Turin), at the Mussa Alp, near the essonite locality. Beautiful honey-yellow and green dodecahedra in cavities of a massive greenish pyroxene (so-called "mussaite") which traverses the serpentine. This garnet is known as "topazolite."

Rome.—At **Frascati** loose black dodecahedra with truncated edges, doubtless derived from the piperno of the **Alban Mountains.** These are known as "melanite."

Pyrenees.—Small black dodecahedra ("pyreneite") in a dark-coloured limestone; these show a zonal structure under the microscope, and are biaxial in parts.

Sisertsk (Urals).—Bright green nodules with chrysotile, dolomite, and magnetite in a serpentinous rock. A similar green garnet in rolled fragments is also found at **Nizhni-Tagilsk.** These are known as "demantoid." This beautiful mineral is cut as a gemstone, and is commonly sold as "olivine."

Arendal (Norway).—Brown dodecahedra in calcite among the magnetite deposits.

ZIRCON

Zircon.—Silicate of zirconium; $ZrSiO_4$; $ZrO_2 = 67{\cdot}2$, $SiO_2 = 32{\cdot}8$. Tetragonal; holosymmetric.

$$a : c = 1 : 0{\cdot}640.$$

$$p = \{111\},\ A = \{100\},\ m = \{110\},\ x = \{311\}.$$

$$pp\ (111) : (1\bar{1}1) = 56^\circ\ 40',\ mp\ (110) : (111) = 47^\circ\ 50'.$$

Cleavage $\{111\}$, $\{110\}$, imperfect. Brittle. Fracture, conchoidal. $H = 7\frac{1}{2}$; $G = 4{\cdot}7$. Brown. Streak, colourless. Lustre, adamantine. Subtranslucent; $\omega = 1{\cdot}931$. Birefringence, positive, strong; $\epsilon - \omega = 0{\cdot}062$. Infusible. Insoluble in acids.

With the above description compare crystals from **Miask** in the Urals.

Zircon is isomorphous with the oxides, cassiterite and rutile, and for this reason is often placed in the same group with them among the

oxides. It is an important (accessory) rock constituent, especially in the more acid eruptive rocks, and having been one of the earliest minerals to solidify, is always in crystals; it is found in crystals of considerable size in elæolite-syenite and augite-syenite, and in small or microscopic

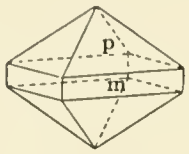

Fig. 650.—Zircon, *m* {110}, *p* {111}.

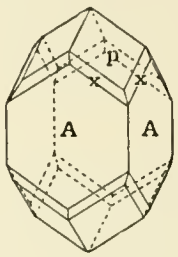

Fig. 651.—Zircon, A {100}, *p* {111}, *x* {311}.

crystals in a great variety of igneous rocks, and in the crystalline schists, and especially in gneiss. Being little liable to decomposition, it is often found in small crystals in sands and other materials derived from the destruction of any of these rocks; it is common among the heavy constituents of auriferous and gem sands.

Zircon crystals are almost always a combination of a square prism, or of the two square prisms A, *m*, with a square pyramid, the habit being either pyramidal, as in Fig. 650, or more prismatic, as in Fig. 651; in microscopic crystals usually the former. A large development of the form *x* sometimes gives them an acute termination.

It is one of those minerals, like quartz and cassiterite, on which the basal plane is very rarely developed.

The close resemblance between zircon and the rutile group is displayed in their angles; *pm* (111):(110) is 47° 50′ for zircon, 47° 40′ for rutile, 46° 27′ for cassiterite; this resemblance is shared by another mineral of analogous composition, which is neither oxide nor silicate, namely, the rare phosphate xenotime, so that the following series must be regarded, if not as isomorphous in the strict sense, at least as analogous both in form and composition.

Cassiterite	$SnSnO_4$
Rutile	$TiTiO_4$
Zircon	$ZrSiO_4$
Thorite	$ThSiO_4$
Xenotime	YPO_4

It was always a matter of surprise that zircon did not twin, like rutile, on (101), until about 1881 crystals like Fig. 652 were found in a crystalline limestone in Renfrew County, Ontario (Canada), which are twinned, and on this very law.

Zircon is recognisable under the microscope by its very high refraction and birefringence; when mounted in Canada balsam it exhibits a marked relief, and in ordinary rock sections gives interference tints of the third or higher orders. A basal section of a zircon crystal rarely gives a normal uniaxial figure, the black cross being broken into

hyperbolic brushes. Some accordingly regard the crystals as mimetic twins of monoclinic individuals; the effect is often associated with well-marked zonal structure.

Its hardness, high refractive index, and great dispersion render zircon a valuable gem; in refraction and dispersion it comes next to the diamond among precious stones; it further possesses a very great range of colour. The ordinary crystals are dark brown, but even among the clear varieties suitable for gems are to be found also colourless stones, and various shades of orange, yellow, red (jacynth), pale green and gray (jargoon). The colour is probably due to a trace of Fe_2O_3, and it can be altered by heating in the oxidising or reducing flame. The specific gravity can also, generally, be raised by heating. Zircon is, as mentioned on p. 276, one of the minerals which gives a characteristic absorption spectrum (Fig. 415); this appears to be almost constant for zircons of different colours; it may be due partly to uranium.

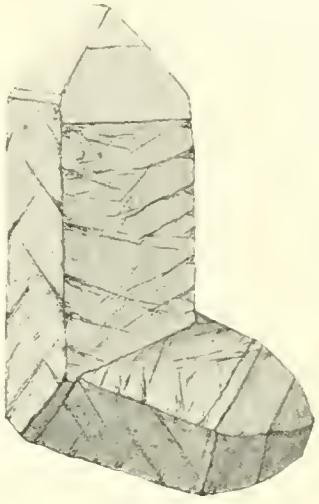

Fig. 652. — Zircon twinned on (011), from Ontario.

Although very stable, and only attacked with difficulty by hot sulphuric acid, zircon is liable to hydration in nature, and several altered varieties which have acquired a vitreous or greasy lustre are known by special names.

Among characteristic occurrences may be mentioned those of Fredriksvärn and similar localities in Norway, where zircon is a constituent of the "zircon-syenite" in crystals of the habit of Fig. 651, associated with orthoclase, elæolite, etc.; the Ilmen Mountains in the Urals, where it occurs in crystals of prismatic habit in veins of the granite associated with orthoclase, mica, apatite, etc. Colourless zircon is found in small crystals in drusy cavities in the trachytic ejections of Laach in the Eifel; also in beautiful crystals, like Fig. 651, associated with pink titanite and chlorite in the Pfitschthal in the Tyrol. From Ceylon come fine gemstones.

SECTION XXV

THE PHOSPHATES

THE APATITE GROUP

Apatite.—Fluo-phosphate of calcium; $Ca_5F(PO_4)_3$; $CaO = 55{\cdot}5$, $P_2O_5 = 42{\cdot}3$, $F = 3{\cdot}8$. Hexagonal; symmetry, hexagonal equatorial.

$$a : c = 1 : 0{\cdot}7346.$$

$$m = \{10\bar{1}0\}, C = \{0001\}, x = \{10\bar{1}1\}, s = \{11\bar{2}1\}, \mu = \{21\bar{3}1\}.$$

Cx $(0001) : (10\bar{1}1) = 40^\circ\ 18'$, Cs $(0001) : (11\bar{2}1) = 55^\circ\ 45'$, xx $(10\bar{1}1) : (01\bar{1}1) = 37^\circ\ 44'$, $m\mu$ $(10\bar{1}0) : (21\bar{3}1) = 30^\circ\ 20'$, ms $(10\bar{1}0) : (11\bar{2}1) = 44^\circ\ 17'$, mx $(10\bar{1}0) : (01\bar{1}1) = 71^\circ\ 8'$.

Cleavage m, C, imperfect. Brittle. Fracture, conchoidal. $H = 5$; $G = 3{\cdot}2$. Colourless. Streak, white. Lustre, vitreous. Transparent; $\omega = 1{\cdot}646$. Birefringence, weak, negative; $\omega - \epsilon = 0{\cdot}004$. Fusible with difficulty (5). Decomposed by hydrochloric acid.

With the above description compare crystals from **St. Gothard**.

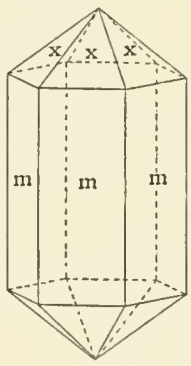

Fig. 653.—Apatite, m $\{10\bar{1}0\}$, x $\{10\bar{1}1\}$.

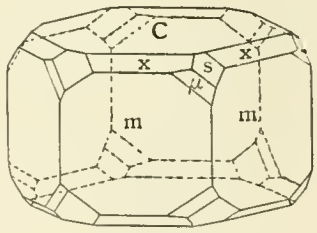

Fig. 654.—Apatite, m $\{10\bar{1}0\}$, C $\{0001\}$, x $\{10\bar{1}1\}$, s $\{11\bar{2}1\}$, μ $\{21\bar{3}1\}$.

Apatite is a widespread mineral of considerable scientific and commercial importance. It was distinguished from tourmaline, fluor, beryl and chrysolite (minerals with which it had previously been confused) in 1775 by Werner, and was found by Klaproth to consist of phosphate of lime; the name is derived from *ἀπατάω*, I deceive. The essential presence of Cl or F in apatite was first proved by Rose in 1827.

Large opaque crystals of apatite are found in metamorphic limestones; those from Canada are sometimes more than a foot in length. Such crystals may be of various shades of blue, green, yellow, or brown, and are generally simple combinations of prism and pyramid (Fig. 653), with or without the basal plane, and are often doubly terminated. Smaller but more perfect crystals occur in the druses of the crystalline schists, and with other fluoriferous minerals in the tin-bearing veins in granites. The most perfect crystals are the little limpid prisms from St. Gothard, which exemplify the hexagonal symmetry of the mineral (Fig. 654). Here the edges between *m* and C are replaced by a series of pyramids, and each corner may bear a face of the form *s*; but besides these are generally found one or more faces, such as μ, in the zone *msx*, lying between *m* and *s*. These faces, though at both ends of the crystal, are situated on one side alone of the prism edge. In this they differ from the trapezohedral faces of quartz, which lie on opposite sides of the prism edge, at the upper and lower ends of the crystal (Fig. 192, p. 75).

Twins of apatite are almost unknown; it has been stated that some apparently holosymmetrical crystals are in reality supplementary twins.

The hexagonal equatorial symmetry of apatite is also made clear by etching with hydrochloric acid (Fig. 273, p. 113).

Ordinary apatite is distinguished from beryl by its inferior hardness and by its cleavage.

Apatite in microscopic crystals is a very widespread constituent of igneous rocks of all sorts; these are generally long hexagonal prisms or needles, which have been one of the first minerals to crystallise; they can be recognised by the imperfect C cleavage, the weak birefringence, and the fairly high refractive index.

Some apatite is biaxial with a small axial angle, but this peculiarity is not so marked as in the other members of the apatite group; it may sometimes be due to isomorphous intermixture with them.

From the chemical point of view two sorts of apatite are to be distinguished—fluor-apatite and chlor-apatite; the first corresponds to the formula given above, while in some varieties the fluorine is entirely replaced by chlorine; there are also intermediate varieties containing both chlorine and fluorine, which are to be regarded as isomorphous mixtures of the two. Of the pure compounds fluor-apatite is more common than chlor-apatite; some varieties contain small proportions of water due to the replacement of Cl and F by OH. On the other hand, several analyses have given a deficiency of Cl or F, and it has consequently been supposed that in these chlorine and fluorine have been replaced by oxygen. Expressed as an ortho-phosphate the formula of apatite is $Ca_4(CaF)(PO_4)_3$, and in this case the corresponding oxygen compound would be $Ca_8(Ca_2O)(PO_4)_6$. Almost pure chlor-apatites occur in Norway, where they constitute beds in the metamorphic limestone.

Massive apatite is mined on a large scale at Odegarden in Norway, where it occurs in veins consisting of apatite, hornblende, enstatite, and black mica in a gabbro which is rich in scapolite near these veins. The

mineral is chlor-apatite. Apatite is very largely worked for use as a manure, but the materials mined for this purpose are mainly the massive, concretionary or earthy varieties, which occur in enormous quantities in several parts of the world; these are white or pale-coloured amorphous deposits, and are totally unlike crystallised apatite in appearance. The impure massive phosphate is often known as "phosphorite." Many of these commercial phosphates are of organic origin; the phosphatic nodules which occur in the Greensand of Cambridge and other places were formerly supposed to be the excreta of extinct mammalia; but though probably of organic origin, they are usually nodular concretions

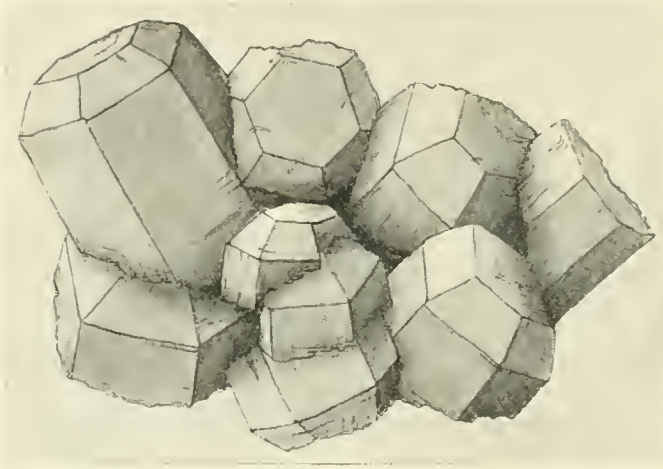

Fig. 655.—Apatite (altered) from Norway.

due to the concentration of phosphatic material previously disseminated through the sand. A phosphate of lime of more recent organic origin is the "guano" found in vast deposits in Chili, Peru, Africa, etc.

Some Noteworthy Localities:

Knappenwand (Untersulzbachthal).—The most beautiful crystals of apatite yet discovered have been found here in cavities of an epidote- or chlorite-schist accompanied by fine dark green crystals of epidote, adularia, and a pale green hair-like asbestos. The apatite is limpid, of thick tabular habit, very rich in faces, and sometimes encloses the asbestos.

St. Gothard.— Little glassy crystals, like Fig. 654, very rich in brilliant faces, and showing very clearly the hexagonal (as contrasted with dihexagonal) symmetry, occur in clefts of the granitic rock associated with adularia, albite, mica, and quartz.

Ehrenfriedersdorf (Saxony). — In the tin mines of the granite beautiful violet fluor-apatite occurs in druses of this rock accompanied by deep violet fluor, cassiterite, quartz, mispickel, and the yellowish micaceous mineral known as "gilbertite." The apatite is mostly in simple combinations, pinakoid $\{0001\}$ with the two prisms $\{10\bar{1}0\}$ and $\{11\bar{2}0\}$, the prisms vertically striated; small pyramid faces also occur. The apatite is sometimes banded with different shades of violet and green.

Very similar crystals are found in the tin mines of **Schlaggenwald** in Bohemia with cassiterite, quartz, fluor, chalcopyrite and earthy kaolin.

Luxullian (St. Austell, Cornwall).—The granite quarries have sometimes furnished brilliant bluish prisms of fluor-apatite; these occur in druses of the white granite which are lined with kaolinised orthoclase and greenish gilbertite; drusy purple fluor accompanies the apatite, which is either in stout hexagonal tables or in long prisms, both habits displaying numerous pyramid faces.

Jumilla (Murcia, Spain).—In cavities of a reddish decomposed volcanic rock associated with hæmatite and calcite, are pale greenish yellow, rough prisms of apatite; these are often doubly terminated, generally without the basal pinakoid (Fig. 653), and exhibit the prism faces $\{10\bar{1}0\}$ and $\{11\bar{2}0\}$. This variety of apatite is known as "asparagus stone" (*Germ.* Spargelstein); it contains both fluorine and chlorine.

Burgess (Ontario, Canada).—In the limestone associated with the Laurentian gneiss here and in other parts of Canada, apatite is largely worked; it is accompanied by pyroxene, amphibole, titanite, zircon, garnet, etc. The dull bluish-green varieties of apatite are known as "moroxite." Prisms of this variety, sometimes doubly terminated (Fig. 653), are found embedded in a pink limestone at Burgess. A similar green moroxite is found in the limestone of **Arendal** (Norway).

The apatite group consists of the following members:—

		c.
Apatite	$(CaF)Ca_4(PO_4)_3$	0·735
Pyromorphite	$(PbCl)Pb_4(PO_4)_3$	0·736
Mimetite	$(PbCl)Pb_4(AsO_4)_3$	0·722
Vanadinite	$(PbCl)Pb_4(VO_4)_3$	0·712
Svabite	$(CaF)Ca_4(AsO_4)_3$	0·714

Pyromorphite.—Chloro-phosphate of lead; $Pb_5Cl(PO_4)_3$ or $(PbCl)Pb_4(PO_4)_3$; $PbO = 82·3$, $P_2O_5 = 15·7$, $Cl = 2·6$. Hexagonal; symmetry, hexagonal equatorial. $Cx = (0001) : (10\bar{1}1) = 40° 22'$. Cleavage *m*, *x*, imperfect. Brittle. Fracture, sub-conchoidal. $H = 3\frac{1}{2}$; $G = 7$. Green. Streak, white. Lustre, resinous. Translucent; $\omega = 1·51$. Birefringence, weak, negative; $\omega - \epsilon = 0·006$. Easily fusible ($1\frac{1}{2}$). Soluble in nitric acid.

With the above description compare crystals from **Ems** (Nassau).

Mimetite.—Chloro-arsenate of lead; $Pb_5Cl(AsO_4)_3$ or $(PbCl)Pb_4(AsO_4)_3$: $PbO = 74·96$, $As_2O_5 = 23·20$, $Cl = 2·39$. Hexagonal (?); symmetry, hexagonal equatorial. $Cx = (0001) : (10\bar{1}1) = 40° 54'$. Cleavage *x*, imperfect. Brittle. Fracture, sub-conchoidal. $H = 3\frac{1}{2}$; $G = 7$. Yellow. Streak, white. Lustre, resinous. Translucent. Birefringence, weak, positive; $\epsilon - \omega = 0·020$. Easily fusible (1). Soluble in nitric acid.

With the above description compare crystals from **Johanngeorgenstadt** (Saxony).

Vanadinite.—Chloro-vanadate of lead; $Pb_5Cl(VO_4)_3$ or $(PbCl)Pb_4(VO_4)_3$; $PbO = 78·7$, $V_2O_5 = 19·36$, $Cl = 2·5$. Hexagonal: symmetry, hexagonal equatorial. $Cx = (0001) : (10\bar{1}1) = 39° 26'$. Cleavage, none. Brittle. Fracture, uneven.

H = 3; G = 7. Red. Streak, nearly white. Lustre, resinous. Translucent. Birefringence weak, negative; $\omega - \epsilon = 0{\cdot}010$. Easily fusible. Partly soluble in hydrochloric or nitric acid.

With the above description compare crystals from **Arizona**.

Pyromorphite (πῦρ, fire; μορφή, form) (*Germ.* Grünbleierz) was so named by Hausmann because when fused by the blowpipe the globule solidifies with facets; the mineral was known as a lead ore under the name of Grünbleierz or Braunbleierz. Klaproth first proved the green mineral from Zschopau in Saxony to be a phosphate.

Mimetite was not distinguished from pyromorphite until the analyses of Rose and Wöhler; the name (μιμητής, an imitator) was given in allusion to its resemblance to pyromorphite.

Vanadinite (*Germ.* Vanadinbleierz) from Mexico was first examined (1801) by Del Rio, who found it to contain a new element, to which he gave the name erythronium, and this was afterwards supposed to be chromium; it was not till 1830 that Wöhler showed this element to be identical with vanadium, which had subsequently been discovered in Swedish iron.

These three minerals, with apatite, constitute a very perfect isomorphous series, each being capable of intermixture with the others; the isomorphism of vanadinite with pyromorphite led to the researches of Roscoe, which proved that oxide of vanadium is not VO_3 but V_2O_5, corresponding to P_2O_5.

They all occur in crystals which are usually a combination of hexagonal prism and basal plane, the edges being sometimes replaced by pyramid faces; that the symmetry is hexagonal and not dihexagonal has been shown by etching in the case of pyromorphite and mimetite, which both yield figures like those of Fig. 273, p. 113. Vanadinite is a mineral richer in faces, and sometimes shows $\{2\bar{1}31\}$ disposed like μ in Fig. 654, and so indicating the true symmetry of the mineral. Pyromorphite and mimetite are not rare minerals, since they are found in considerable quantities in the upper levels of many lead mines, where they have doubtless been derived from the decomposition of galena. They range over a great variety of colour, especially different shades of brown, gray, green, and yellow; some orange-coloured varieties of pyromorphite are said to contain chromium, but other yellow and orange specimens (*e.g.* those from Scotland, Cumberland, and Cornwall) seem to be free from that element; some of the varieties containing lime, *i.e.* isomorphous mixtures with apatite, are pale brown or yellow or even almost white. Isomorphous intermixtures of pyromorphite and mimetite are much more common; the pyromorphites from Cumberland contain about 9 per cent of As_2O_5. These two minerals are in fact difficult to distinguish except by chemical tests; the mining names, Braunbleierz, Grünbleierz, Buntbleierz, refer indiscriminately to both minerals and to their mixtures. They both possess the resinous lustre so characteristic of minerals containing lead. The presence of arsenic is indicated by the deposit obtained by heating a fragment of the mineral with charcoal

in a closed tube, and the amount of arsenic serves to distinguish the two species. Both minerals give evidence of chlorine by the blue colour imparted to flame when heated in the oxidising flame in microcosmic salt which has been saturated with oxide of copper. The facetted globule yielded by the fusion of pyromorphite, and alluded to in its name, seems to be characteristic; the facets are not crystal faces. The test for arsenate or phosphate is best made by the ordinary methods with the nitric acid solutions of these two minerals.

Both pyromorphite and mimetite tend to form barrel-shaped crystals by aggregation and by the curvature of the prism faces. Many specimens of these minerals are in crystalline aggregates or in mamillary or concretionary forms. Some of the varieties of pyromorphite containing lime are so persistently globular that they have received the name "polysphærite." The yellow, brown, and red mimetite found at Roughten Gill in Cumberland (Fig. 656) was for this reason called campylite (from *καμπύλος, curved*); it contains more than 3 per cent of P_2O_5.

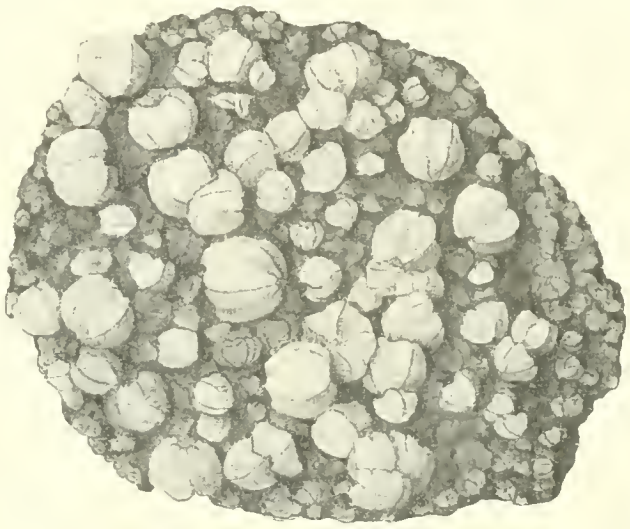

Fig. 656.—Mimetite (campylite) from Cumberland.

A white mineral of resinous lustre found at Langban in Sweden and known as **hedyphane**, appears to be an isomorphous mixture of mimetite with pyromorphite, apatite, and an analogous *barium* compound; for it contains up to 8 per cent of BaO, and varying proportions of CaO. Crystals of this mineral have been found to have angles near those of the apatite group. That it is biaxial is no argument for excluding it from the group, for the other minerals exhibit so-called optical anomalies.

Pyromorphite is often biaxial; a basal section may be uniaxial in the centre and biaxial at the edges, and it is possible that this may be related to the tendency of the crystals, mentioned above, to aggregate themselves in a slightly radiating manner, as in campylite.

Mimetite is always biaxial; a basal section is seen to be composed of six triangular sectors, in each of which the axial plane ($2E = 40^\circ - 60^\circ$) is parallel to the prism edge.

The intermediate mixtures of pyromorphite and mimetite are biaxial, and this property increases with the proportion of mimetite present, and therefore may be considered to be due to the latter.

The pyromorphite from Roughten Gill seems to consist in the middle of uniaxial pyromorphite and at the sides of biaxial mimetite. Since, however, pure mimetite is almost unknown, the biaxiality of this mineral may be really due to strains set up by isomorphous intermixture.

Some of the finest distinct crystals of pyromorphite are the large hexagonal prisms of dull violet colour found in the lead mines of Poullaouen in Brittany. These, as mentioned on p. 316, are sometimes converted into galena.

Brilliant pale green or yellow translucent crystals were formerly found lining cavities in a ferruginous vein-quartz at Huel Alfred near Camborne in Cornwall.

Vanadinite has been found in lustrous red or yellow prisms in Mexico and in Arizona; these often bear pyramid faces as well as the basal pinakoid; the crystals are sometimes hollow. The mineral can be identified by the colour, characteristic of vanadium, given to a bead of microcosmic salt.

A variety, called "endlichite," found in brilliant gray crystals at Lake Valley (New Mexico), contains from 11 to 13 per cent of As_2O_5, and may be regarded as an isomorphous mixture of vanadinite and mimetite.

Svabite, a rare mineral, only found in small colourless prisms at the manganese mines of Pajsberg and Nordmark in Sweden, appears to be the calcium arsenate, $(CaF)Ca_4(AsO_4)_3$, analogous to apatite; it is further interesting as containing both Cl and (OH) partially replacing the fluorine.

A considerable number of phosphates are known as minerals, especially basic compounds; they do not for the most part fall into isomorphous groups. The two best defined are the olivenite and the vivianite groups.

THE OLIVENITE GROUP

Olivenite is a copper arsenate formerly found in abundance in the copper mines of Cornwall, sometimes as olive-green orthorhombic prisms, {110}, {100}, {010}, terminated by the combination {101} {011}, which together resemble a square pyramid; $(110):(1\bar{1}0) = 86° 26'$.

It occurs more usually in fibrous aggregates of acicular crystals which often present a beautiful velvety surface. This variety is known as "wood copper" (*Germ.* Holzkupfererz). Some specimens are quite soft and almost earthy. The colour of olivenite varies very widely through many shades of green, brown, and yellow, and the "wood copper" is sometimes almost white. Composition $(CuOH)Cu(AsO_4)$, the water being given off only at a high temperature; some As_2O_5 is replaced by P_2O_5.

To the same group with olivenite belong the following:—

Libethenite . . .	$(CuOH)Cu(PO_4)$.
Adamite . . .	$(ZnOH)Zn(AsO_4)$.
Descloizite . . .	$(PbOH)Pb(VO_4)$.

Libethenite is a mineral of the same forms and habit as olivenite, only of a darker green colour, which occurs in good crystals at Libethen in Hungary.

Adamite is found in crystalline crusts at the zinc mines at Laurium near Athens, which have furnished a number of interesting zinc minerals. It varies widely in colour owing to the presence of copper and cobalt, and may be white, yellow, red, blue, or green.

In olivenite, libethenite, and adamite, the axial plane is (001), and the axial angle about 80°, so that an optic axis is visible through each face of the prism {110}, and is nearly perpendicular to the face.

Descloizite occurs in small, lustrous, deep red, almost black, crystals at Lake Valley (New Mexico), already mentioned as the locality of endlichite. Vanadium is partially replaced by arsenic and phosphorus, and lead by zinc and copper.

THE VIVIANITE GROUP

Vivianite, $Fe_3(PO_4)_2 . 8H_2O$, is a mineral belonging to the monoclinic system, which has been found in beautiful translucent steely indigo-blue prisms, *e.g.* in pyrrhotite at St. Agnes (Cornwall); the crystals have a highly perfect cleavage parallel to the plane of symmetry (010), and a pearly lustre on that face; the lustre is vitreous on other faces. Vivianite is flexible and sectile. The obtuse negative bisectrix is perpendicular to the cleavage face, and there is strong pleochroism. Analyses show the presence of Fe_2O_3, but this and the colour are due to subsequent oxidation, for at Delaware in Pennsylvania have been found *colourless* crystals containing only FeO and not Fe_2O_3, and these change their colour on exposure and become blue. Vivianite is also found as a blue earthy mineral. This earthy variety, which is of a paler colour than the crystals, occurs as a decomposition product of other iron minerals accompanying fossils and organic remains; it often gives a blue colour to bog-iron-ore and other ferriferous deposits.

To the same isomorphous group belong the corresponding arsenates of iron and cobalt, which are found crystallised, and probably also the corresponding arsenates of magnesium, nickel, and zinc, and the phosphate of magnesium; but these latter are all too imperfectly crystallised to admit of measurement.

The arsenates of cobalt and nickel are fairly common minerals:—

Erythrite, $Co_3(AsO_4)_2 . 8H_2O$, is a beautiful crimson mineral occurring in crystals like those of vivianite, with the same cleavage and flexibility, and the negative acute bisectrix perpendicular to the cleavage; but it is usually found as a peach-coloured earthy mineral known as "cobalt bloom" (*Germ.* Kobaltblüthe or Kobalt-beschlag), corresponding to the earthy vivianite.

Annabergite, $Ni_3(AsO_4)_2 . 8H_2O$, is an apple-green mineral, found almost exclusively as the corresponding earthy "nickel bloom" (*Germ.* Nickelblüthe).

Erythrite and annabergite are the common decomposition products of minerals containing cobalt or nickel, and are easily recognised by their characteristic colours, serving as certain indications of the presence of those metals.

Among the other hydrated phosphates the aluminium compounds wavellite and turquoise deserve mention.

Wavellite, $2(AlOH)_3(PO_4)_2 . 9H_2O$, belongs to the orthorhombic system, but almost always occurs in radiated aggregates giving rise to globular or botryoidal forms, Fig. 394, p. 249. The mineral is named after its discoverer, Dr. Wavel, by whom it was found lining fissures in slate, near Barnstaple in Devonshire. It is translucent, and generally white or gray, but also assumes various shades of green, yellow, or brown. It is one of the best examples of radiated structure. Wavellite usually contains fluorine.

Turquoise or callaite (*Germ.* Türkis), $Al_2(OH)_3PO_4 . H_2O$, is only known as a massive mineral, as an encrustation, or in reniform nodules. The true oriental turquoise, valued in jewellery, is found in a brecciated porphyritic trachyte near Nishapur in Persia; together with limonite, the sky-blue turquoise fills cavities and crevices in this breccia, or is found as nodules in the decomposed rock. The name turquoise may be derived from "Turkey" through the French, or may be a corruption of the Persian name Piruzeh. Callaite is from *callais*—the name used by Pliny for a green stone brought from beyond India. It is probable that turquoise was always prized as a gem. In the turquoise of most localities the colour varies from sky-blue to pale apple-green. It has lately been found at several localities in New Mexico (Burroo Mountains and Jarilla Mountains) as seams and nodules in trachyte. $G = 2{\cdot}7$; $H = 6$.

In thin sections turquoise is seen to be not absolutely amorphous like opal, but to consist of very minute birefringent granules. The variations of colour are probably due to phosphate of iron and copper.

The true "oriental turquoise" is to be distinguished from another substance, known as "bone turquoise" (Zahntürkis) or "occidental turquoise," also called "odontolite," and "turquoise de la nouvelle roche." This, as its name signifies, is of organic origin, and consists of the teeth or bones of extinct mammals, stained probably by the absorption of earthy blue vivianite. It is, and has long been, used as turquoise. In thin sections it is seen to have an organic structure, and the colouring matter follows minute apertures. Bone turquoise contains also $CaCO_3$, and effervesces with acids.

There are numerous phosphates and arsenates of copper, mostly of blue or green colour, which have been found accompanying the ores of copper in the Cornish and Utah mining districts, many of them beautifully crystallised. Among those which contain rare elements may be mentioned **cupro-uranite** (or torbernite), $Cu(UO_2)_2(PO_4)_2 . 8H_2O$ which resembles the vivianite group in composition. It is a beautiful mineral, occurring in vivid emerald-green square plates belonging to the tetragonal system, with a perfect basal cleavage. The corresponding calcium compound **calco-uranite** (or autunite) is very similar, but paler

in colour, and is pseudo-tetragonal, giving a biaxial figure through the cleavage plate.

Monazite, the rare phosphate of didymium (Ce,La,Di)PO_4 (containing also thorium), which is now of great commercial importance as a source of the ceria and thoria required for incandescent gas mantles, is found in brown crystals of considerable size in the granite of Arendal in Norway, but the commercial material is worked on a large scale in Brazil and North Carolina, from sands which are rich in grains of the mineral.

Monazite occurs in microscopic crystals, enclosed in the apatite of Arendal. These are left when the apatite is dissolved in nitric acid, and, like all monazite, may be identified by the absorption spectrum of Fig. 414, p. 275.

SECTION XXVI

THE SULPHATES

THE BARYTES GROUP

Barytes.—Sulphate of barium; $BaSO_4$; $BaO = 65{\cdot}7$, $SO_3 = 34{\cdot}3$. Orthorhombic.

$$a : b : c = 0{\cdot}815 : 1 : 1{\cdot}314.$$

$$A = \{100\},\ C = \{001\},\ m = \{110\},\ d = \{102\},\ o = \{011\},$$
$$y = \{122\},\ z = \{111\}.$$

$mm\ (110) : (1\bar{1}0) = 78^\circ\ 23'$, $Cd\ (001) : (102) = 38^\circ\ 51'$, $Co\ (001) : (011) = 52^\circ\ 43'$, $Cz\ (001) : (111) = 64^\circ\ 19'$, $oy\ (011) : (122) = 26^\circ\ 1'$, $oz\ (011) : (111) = 44^\circ\ 18\frac{1}{2}'$.

Cleavage m, C, perfect. Brittle. Fracture, uneven. $H = 3$; $G = 4{\cdot}5$. Colourless. Streak, white. Lustre, vitreous. Transparent; $\beta = 1{\cdot}637$. Birefringence, strong, positive; $\gamma - \alpha = 0{\cdot}012$. Axial plane (010); acute bisectrix perpendicular to (100); $2E = 64^\circ$, $\rho < v$. Fusible (3), with decrepitation. Not decomposed by acids.

With the above description compare crystals from **Dufton** (Westmorland).

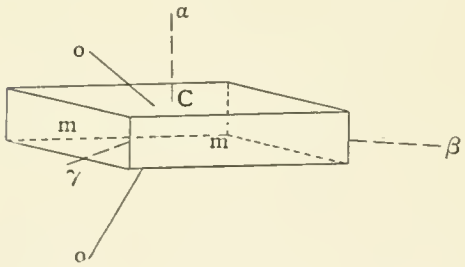

Fig. 657.—Barytes, m {110}, C {001}.

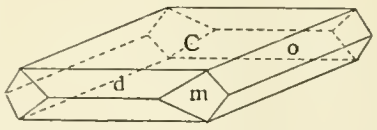

Fig. 658.—Barytes, C {001}, m {110}, d {102}, o {011}.

Barytes, or heavy spar (*Germ.* Schwerspath), is a very common mineral in metalliferous veins, especially those containing lead, silver, and cobalt minerals, both as part of the veinstone and as crystals on the vein walls. It is remarkable that this sulphate, which is one of the most difficult substances to crystallise in the laboratory, should, as a mineral, furnish some of the most beautiful of crystallised specimens.

Commercially it is of considerable importance as the source of barium compounds, and as a white pigment ("permanent white"); for the latter purpose, however, it is mixed with white lead on account of its insufficient opacity.

Barytes is easily recognised by its weight and cleavage (the name is

derived from *βαρύς*, heavy). The cleavage form C*m* (Fig. 657) is not unusual as a crystal combination, *e.g.* at Felsöbanya (Fig. 660), but barytes is generally elongated in the direction of the *a*-axis, and bounded laterally by the form *o*, which is very common. The habit is variable — some crystals are elongated along the *b*-axis, and many are very rich in faces, but they can always be correctly orientated by means of the cleavages; the C cleavage is usually visible as pearly cracks giving the interference tints of thin films.

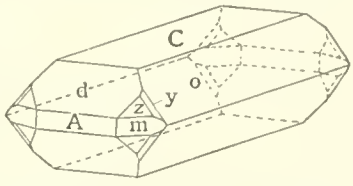

Fig. 659.– Barytes. C {001}, *d* {102}, A {100}, *o* {011}, *m* {110}, *z* {111}, *y* {122}.

Crystals elongated along the *c*-axis are so rare that when they were first discovered (at Betler in Hungary), they were supposed to be a new mineral, and received the name "wolnyn." Similar crystals have been found in Cornwall and in Virginia.

In most localities barytes is white and only translucent, and the crystals are often stained brown or red with oxide of iron; some of the transparent crystals are yellow, brown, or even blue.

The common barytes of the Derbyshire lead mines and many other localities is an aggregate of white, opaque, platy crystals, somewhat rounded and arranged in parallel groups. They resemble a flat rhombohedral combination. This barytes is generally known as "cawk." Another common variety is that known as "crested" or "cockscomb barytes," generally rounded aggregations of tabular crystals like Fig. 657, with the acute prism edges of the crystals projecting from the mass. Ordinary massive barytes is an opaque white material with a platy structure, the plates being often curved. All these, and even the radiated (*Germ.* Strahlbaryt) and columnar (*Germ.* Stangenspath) varieties, may be recognised by the weight and cleavage. The mineral also occurs as a white earthy substance. Crystals of witherite, for example, are often altered on the surface to white earthy or minutely crystalline barytes. The "Bologna stone," found as fibrous concretions in clay, near Bologna, attracted much attention at the beginning of the seventeenth century, when it was discovered that, after heating with charcoal, it possesses the property of becoming luminous in a dark room after exposure to the sun's rays. This was the first observation of inorganic phosphorescence. The property belongs to the barium sulphide, to which the mineral is reduced by heating with charcoal. It is noteworthy that the fibres of Bologna stone are elongated along the vertical axis; most fibrous barytes is elongated along the *a*-axis.

Some barytes, especially massive, possesses repeated twin lamellæ parallel to *m* and *o*; the latter can be observed as striations on *m*, and sometimes give rise to an apparent cleavage parallel to *o*. It is believed that these are planes of secondary twinning due to pressure, for they are rarely observed in barytes which has crystallised out freely in veins or cavities.

Barytes is sometimes differently terminated at the two ends, and some observers have concluded from pyro-electric and etching experi-

ments that it is polar; but the apparent polarity is exhibited *both* along the *a*- and *c*-axes, and subsequent experiments with sodium carbonate and hydrochloric acid have yielded holosymmetric etched figures.

Barytes is generally fairly pure, but often contains a little strontium sulphate and calcium sulphate, the former doubtless owing to isomorphous intermixture with celestite. Before the blowpipe the barium is indicated by the green colour imparted to the flame, and the sulphur by the ordinary test after fusion with sodium carbonate on charcoal.

Although the mineral is for ordinary purposes insoluble in water, it has evidently been, in many instances, deposited by aqueous agency; thus near Nottingham it constitutes the cementing material of a sandstone, and it is sometimes deposited from mine waters containing barium chloride.

Some Noteworthy Localities:

Dufton (Westmorland).—Fine crystals have been found in the lead mines of this district, including some of the largest yet discovered. They are generally of the habit of Fig. 658, and are white, yellow, or brown. Some of these found in a mud were completely terminated.

Liskeard (Cornwall).—Beautiful pale yellow crystals of tabular habit were formerly found in the silver-lead mines in this neighbourhood, associated with iron pyrites and fluor. They sometimes have prominent faces of {111}. Somewhat similar crystals were found in the copper mines of Gwennap.

Egremont (Cumberland).—Associated with the lustrous calcite found in hæmatite, are pale blue tabular crystals of barytes. At Frizington have lately been found brownish-yellow crystals elongated along the *a*-axis, somewhat rounded owing to the development of curved acute pyramid faces nearly coincident with *o*. The basal pinakoid is striated parallel to *m*, and *m* is striated horizontally. Crystals from here may contain a nucleus of different habit, *e.g.* the outer crystal may be terminated by *m*, the inner by *ma*.

Fig. 660.—Barytes, with Stibnite, from Felsöbanya.

Newhaven (near Youlgreave in Derbyshire).—Deep brown stalactitic barytes, with a radiating structure diverging from the axis of the stalactite. This also shows beautiful annular markings, and has been much used for ornamental purposes.

Nutfield (Surrey).—Beautiful honey-yellow crystals, doubly terminated, and of a habit similar to that of Fig. 659, are here found in Fuller's earth.

Felsöbanya (Hungary).—Fine tabular crystals, *C m x d o*, occur with stibnite, quartz, pyrites, blende, etc. They are either white or of various shades of blue and red, or are sometimes coloured yellow by impregnation with orpiment. These crystals are sometimes apparently polar in the direction of the *b*-axis, owing to the development of *m*, *z*, *y* on only one side. The barytes is sometimes penetrated by the needles of stibnite, as shown in Fig. 660.

The barytes group contains the following minerals :—

Barytes	. $BaSO_4$.	$a:b:c = 0{\cdot}815:1:1{\cdot}314$
Celestite	. $SrSO_4$.	$0{\cdot}779:1:1{\cdot}280$
Anglesite	. $PbSO_4$.	$0{\cdot}785:1:1{\cdot}289$

Celestite. — Sulphate of strontium ; $SrSO_4$; $SrO = 56{\cdot}4$, $SO_3 = 43{\cdot}6$. Orthorhombic.

$$a:b:c = 0{\cdot}779:1:1{\cdot}280.$$

$$C = \{001\},\ m = \{110\},\ o = \{011\},\ d = \{102\},\ l = \{104\}.$$

$$mm\ (110):(1\bar{1}0) = 75^\circ\ 50',\ Cd\ (001):(102) = 39^\circ\ 25',\ Co\ (001):(011) = 52^\circ\ 0',$$
$$Cl\ (001):(104) = 22^\circ\ 20'.$$

Cleavage C, perfect ; *m*, good. Brittle. Fracture, uneven. H = 3 ; G = 3·9. Colourless. Streak, white. Lustre, vitreous. Transparent ; $\beta = 1{\cdot}624$. Birefringence, weak, positive ; $\gamma - \alpha = 0{\cdot}009$. Axial plane (010). Acute bisectrix perpendicular to (100) ; $2E = 88^\circ\ 38'$. Fusible (3) with decrepitation. Insoluble in acids.

With the above description compare crystals from **Girgenti** (Sicily).

Anglesite.—Sulphate of lead ; $PbSO_4$; $PbO = 73{\cdot}6$, $SO_3 = 26{\cdot}4$. Orthorhombic.

$$a:b:c = 0{\cdot}785:1:1{\cdot}289.$$

$$m = \{110\},\ C = \{001\},\ o = \{011\},\ d = \{102\},\ y = \{122\},\ z = \{111\}.$$

$$mm\ (110):(1\bar{1}0) = 76^\circ\ 17',\ Cd\ (001):(102) = 39^\circ\ 23',\ Co\ (001):(011) = 52^\circ\ 12',$$
$$yy\ (122):(1\bar{2}2) = 89^\circ\ 48'.$$

Cleavage *m*, C, fair. Brittle. Fracture, conchoidal. H = 3 ; G = 6·3. Colourless. Streak, white. Lustre, adamantine, inclining to resinous. Transparent ; $\beta = 1{\cdot}883$. Birefringence, strong, positive ; $\gamma - \alpha = 0{\cdot}016$. Axial plane (010). Acute bisectrix perpendicular to (100) ; $2H = 89^\circ\ 52'$; $\rho < v$. Easily fusible ($1\frac{1}{2}$). Soluble with difficulty in nitric acid.

With the above description compare crystals from **Monte Poni** (Sardinia).

These sulphates constitute as perfect an isomorphous group as the corresponding series of carbonates, the aragonite group ; but the sulphates are simpler in their crystallisation, being well developed orthorhombic crystals without pseudo-symmetry and devoid of twinning. They all occur in bright glassy crystals of tabular or prismatic habit, and are easily recognised by their three perfect cleavages, two {110} enclosing an angle of 76°–78°, and perpendicular to the third {001} ; the orientation of the indicatrix is also the same for all the three minerals.

Barytes contains both calcium and strontium, and celestite may contain both barium and calcium, but the corresponding calcium sulphate,

anhydrite (see p. 525), can scarcely be regarded as belonging to the same group on account of its difference of form and cleavage.

Although **celestite** (and anglesite), like barytes, occur in a very great variety of combinations, the common crystals are simple; celestite is generally elongated along the *b*-axis, while anglesite may resemble either barytes or celestite in habit, or may be elongated along the vertical axis. Both minerals occasionally occur in acute pyramidal

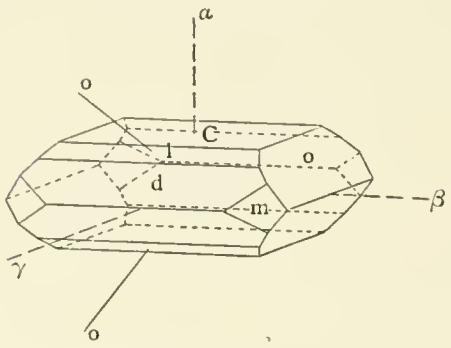

Fig. 661.—Celestite, C {001}, *o* {011}, *d* {102}, *l* {104}, *m* {110}.

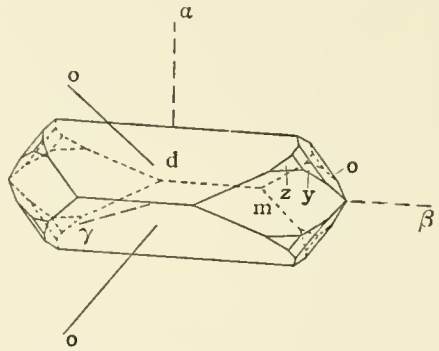

Fig. 662.—Anglesite, *m* {110}, *d* {102}, *o* {011}, *z* {111}, *y* {122}.

crystals formed by brachy-pyramids {*khh*} (144 or 155), which give them quite an unwonted appearance; examples are furnished by large crystals of celestite from Yate in Gloucestershire and from Virginia. Since the discovery of such crystals, it is generally believed that the acute pyramids consisting of granular calcite which have been found at various localities (the "barley-corn pseudomorphs" from Sangerhausen and the so-called "jarrowite" from the Jarrow Docks at Durham and from the Clyde), about which there has been much discussion, are altered celestite or gaylussite.

The name celestite alludes to the bluish tint of the specimens first discovered (in Pennsylvania); it is frequent in this mineral, *e.g.*, at Herrengrund, Salzburg, etc., and may be due to a trace of iron phosphate. Celestite usually occurs in limestones or sandstones or associated with gypsum and rock-salt.

Celestite is of commercial importance as the source of strontium compounds, which are largely used for fireworks, etc., to produce red colours. The strontium in the mineral is easily detected by the red coloration to flame, especially after the fused mass has been treated with hydrochloric acid and alcohol.

Some Noteworthy Localities:

Girgenti (Sicily).—Here colourless crystals, of prismatic habit owing to the predominance of *o*, like Fig. 659 of barytes, are situated upon sulphur or upon crusts consisting of acute rhombohedra of calcite.

Herrengrund (Hungary). — Beautiful blue crystals rich in faces occur in druses in the copper mines; they are often situated upon pseudomorphs of calcite after aragonite; the crystals are either prismatic, like Fig. 659 of barytes, or rhombic plates, like Fig. 657.

Lake Erie.—On **Strontian Island** large crystals of the habit of Fig. 661 are found in the limestone.

Yate (Gloucestershire).—In the triassic marl are found geodes of celestite lined with large, transparent, colourless crystals both of prismatic and tabular habit. These are associated with and sometimes enclosed in gypsum crystals.

Anglesite is named from the locality where it was first found, the island of Anglesey. Here, at the Parys Copper Mine, small, doubly terminated, yellow crystals of the habit of Fig. 662 were found in an earthy brown limonite.

But far finer specimens were subsequently found in the lead mines of Monte Poni in Sardinia, where the mineral has evidently been derived from the alteration of galena; it here occurs in lustrous, transparent, and colourless crystals lining cavities in a glistening granular galena. The crystals are of a great variety of combinations and habits, and are difficult to decipher without measurements of the angles.

Anglesite usually occurs in metalliferous veins as an alteration product of galena.

Two common characteristics of lead minerals distinguish anglesite from the other minerals of the group: its easy fusibility and adamantine or resinous lustre. The lead is easily detected in anglesite by reduction on charcoal; the mineral is an important ore of lead, and is found massive in large quantities in some mining districts.

ANHYDRITE

Anhydrite.—Sulphate of calcium; $CaO = 41{\cdot}2$, $SO_3 = 58{\cdot}8$. Orthorhombic.

$$a : b : c = 0{\cdot}893 : 1 : 1{\cdot}001.$$

$$A = \{100\},\ B = \{010\},\ C = \{001\},\ m = \{110\},\ r = \{011\}.$$

$$mm\ (110) : (1\bar{1}0) = 83^\circ\ 33',\ rr\ (011) : (0\bar{1}1) = 96^\circ\ 30'.$$

Cleavage, A, B, C, perfect. Brittle. Fracture, uneven. $H = 3\frac{1}{2}$; $G = 2{\cdot}9$. Colourless. Streak, grayish. Lustre, vitreous to pearly. Transparent; $\beta = 1{\cdot}576$. Birefringence, strong, positive; $\gamma - \alpha = 0{\cdot}043$. Axial plane (010). Acute bisectrix perpendicular to (100); $2E = 71^\circ\ 30'$; $\rho < v$. Fusible (3). Soluble in hydrochloric acid.

With the above description compare crystals from **Stassfurt** (Prussia).

Anhydrite, so called from its composition, the anhydrous sulphate of lime, is found in large massive deposits associated with gypsum and rock-salt; it is also known as muriacite and karstenite. It is found crystallised at a few localities, *e.g.* Aussee in Styria, in brown crystals of cubic habit, A, B, C, in a mixture of clay, rock-salt, and gypsum; in rock-salt at Stassfurt; and in blue crystals in limestone at Berchtesgaden in Bavaria. The axial ratios and the cleavage are quite different from those of the barytes group, to which it might be expected to belong. The mineral is usually massive, but can even then be recognised by its cleavage. The three cleavage faces are perpendicular to the axes of the indicatrix, and therefore furnish plates in which the appearance of the

interference figures, as viewed along the acute bisectrix, the obtuse bisectrix, and the third mean line, can be conveniently studied. The B cleavage is a little less easy than C, and A than B.

GYPSUM

Gypsum.—Hydrated sulphate of calcium; $CaSO_4 . 2H_2O$; $CaO = 32{\cdot}5$, $SO_3 = 46{\cdot}6$, $H_2O = 20{\cdot}9$. Monoclinic.

$$a : b : c = 0{\cdot}690 : 1 : 0{\cdot}412. \quad \beta = 80^\circ\ 42'.$$

$$B = \{010\},\ e = \{\bar{1}03\},\ l = \{\bar{1}11\},\ m = \{110\},\ k = \{130\}.$$

$$Bm\ (010) : (110) = 55^\circ\ 45',\ ll\ (111) : (1\bar{1}1) = 36^\circ\ 12',\ mm\ (110) : (\bar{1}10) = 68^\circ\ 30',$$

$$Bk\ (010) : (130) = 26^\circ\ 5'.$$

Twinned on (100), also on (101). Cleavage B, perfect; A {100} and n {$\bar{1}11$}, imperfect. Sectile. Flexible. $H = 2$; $G = 2{\cdot}3$. Colourless. Streak, white. Lustre, vitreous. Transparent; $\beta = 1{\cdot}522$. Birefringence, fairly strong, positive; $\gamma - \alpha = 0{\cdot}010$. Axial plane (010). Acute bisectrix inclined at 37° 30′ to the normal of A, and 43° 12′ to the normal of C; $2E = 95^\circ$. Dispersion inclined; $\rho > v$. Fusible (3). Soluble in hydrochloric acid.

With the above description compare crystals from **Bex** (Switzerland).

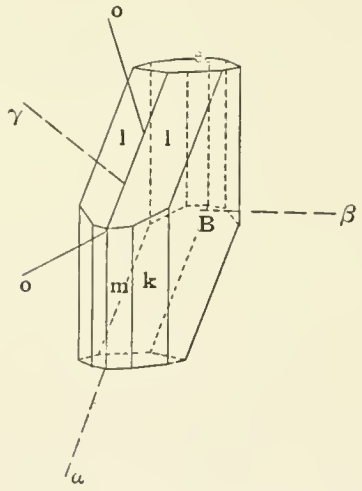

Fig. 663.—Gypsum, B {010}, l {111}, m {110}, k {130}, e {103}.

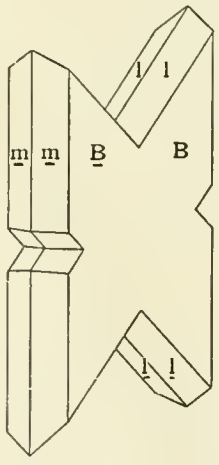

Fig. 664.—Gypsum twinned on (100).

Gypsum, or selenite (*Ital.* Gesso), is a mineral of considerable commercial importance as the source of plaster-of-Paris, which received this name because it was obtained by burning the gypsum from the quarries of Montmartre near Paris; it is also used as a surface dressing for agricultural land. The name is derived from γύψος, which may have denoted burnt gypsum. The name selenite is the *selenites* of Dioscorides and Pliny, which also may have been gypsum; this name is now generally used for the crystallised varieties.

Gypsum occurs in large beds associated with limestones, clays, and marls, and in connection with salt and anhydrite; the best crystals are those which are found in clay (as near Oxford), or lining druses with sulphur (as in Sicily). The crystals are almost always the simple

combination B*ml*, like Fig. 226. At some localities, as at Bex, there is also the face *e*, which is nearly perpendicular to the prism edge (Fig. 663), but this face is generally uneven and curved, sometimes concave. Cleavage flakes parallel to B are flexible, and when bent break along $(\bar{1}01)$, which would be a face at the back of the crystal inclined to the vertical at the angle 66° 10′; but this fracture is fibrous and, if examined closely, is seen to consist of the two imperfect cleavages (111) $(\bar{1}\bar{1}1)$ at the back of the crystal, corresponding to the faces *l* in front; the flakes also break unevenly along the imperfect cleavage (100). The (100) cleavage is known as the "conchoidal" cleavage to distinguish it from the $(\bar{1}11)$ or "fibrous" cleavage; the cracks which these cleavages produce on the face B are inclined to one another at 113° 50′. These cracks serve to orientate a cleavage plate when no crystal faces are present, for the conchoidal cleavage is parallel to the *c*-axis. Other cleavage cracks can also be produced by pressure.

Cleavage plates, B, can be obtained as thin as desired, and are useful to produce interference tints of the different orders; *e.g.* red of the first order; such a plate can be used to detect the weak birefringence in sections of minerals which are nearly isotropic, since it becomes elevated in the scale (to blue) or depressed (to yellow) when the plate is superposed on the mineral section; it may also be used to determine the optical sign (p. 175).

Gypsum is one of those substances whose optical characters vary considerably with change of temperature. At ordinary temperatures the plane of the optic axes is parallel to the plane of symmetry (Fig. 663) and there is strong inclined dispersion. If the interference figure be viewed through a plate cut perpendicular to the acute bisectrix (such a section is difficult to prepare on account of the cleavage), and the plate be warmed, the angle of the optic axes gradually diminishes, until the crystal is uniaxial for blue light; a little later it becomes uniaxial for yellow and then, at 116° C., for red light; meanwhile the optic axes for blue begin to open out in a plane perpendicular to the plane of symmetry (as in Fig. 337), and are followed by those for other colours; at 120° C. the optic axial plane is perpendicular to (010), and the dispersion is no longer inclined but horizontal, with $\rho < v$. It is not safe to raise the temperature any further, since the mineral begins to give off water and become permanently altered.

During this change the acute bisectrix also changes its position, and moves through about $5\frac{1}{2}°$ (between 20° C. and 100° C.) in the plane of symmetry.

Gypsum is also one of the few minerals in which the change of angles between the faces produced by change of temperature, owing to the different expansion in different directions, can be measured. Mitscherlich studied this by cutting a plate from a twin crystal at right angles to the twin plane, and found that on heating such a plate the two halves become inclined to each other by several minutes, owing to the change of angle between the artificial face and the twin plane.

Twinning on the ortho-pinakoid (100) is very common, both by

juxtaposition, Fig. 225, p. 88, and by interpenetration, Fig. 664; here the edges of the prism *mm*, which would be truncated by the twin plane, are parallel in the two individuals. The other law, twin plane (101), gives rise to very similar groups, but here the edges *ll*, which would be truncated by the twin plane, are parallel; the *m* faces are easily distinguished from the *l* faces since they enclose a larger angle.

The twinning on (100) is easily detected, even on cleavage flakes, by the fact that the fibrous cleavage cracks do not run uniformly across the crystal, but meet at an angle of 47° 50′ on the line of contact.

Crystals of gypsum are very apt to be curved or even lenticular (Fig. 392); in twins this sometimes produces arrowhead forms. They may also be coloured gray, yellow, brown, or black by impurities. The long crystals from Gotha are sometimes twisted and bent in a fantastic manner.

Massive gypsum, when of a fine grain, is known as alabaster (from ἀλαβαστίτης), and is used for ornamental purposes; the name is also applied to the white and banded stalagmitic or "onyx-marble" varieties of calcite, and this was probably the material used by the ancients; this is now known as "oriental alabaster."

Gypsum, whether massive or crystallised, is easily distinguished by its softness from this and other minerals which it resembles; it is readily scratched by the finger nail, whereas calcite is not. Fibrous gypsum sometimes forms a beautiful material with a satiny lustre or even a pearly opalescence; it is known by the same name as the fibrous calcite or aragonite, "satin-spar," and is used as an ornamental stone.

Microscopic crystals with the characteristic outline of Fig. 226, and an extinction of $37\frac{1}{2}°$, can be produced by mixing very dilute aqueous solutions of a soluble sulphate and of calcium chloride, or even by the evaporation of sea water, which contains calcium sulphate in solution; but the more usual form of gypsum obtained by rapid crystallisation in microchemical reactions is the tufts of needles shown in Fig. 409.

Some Noteworthy Localities:

Shotover Hill (Oxford).—Large isolated crystals are found in the blue Kimmeridge clay; these are both simple crystals like Fig. 224, and twins like Fig. 225, p. 88, or like Figs. 664 and 665, and are generally more or less opaque owing to included clay.

Very similar crystals are found in the London clay in the **Isle of Sheppey** and other localities; here, as elsewhere, they are frequently associated with iron pyrites and marcasite, and have probably been produced through the decomposition of pyrites in the presence of calcium carbonate (p. 328).

Bex (Switzerland).—Beautiful limpid crystals are here found in the salt mines; they are of the habit of Fig. 663, and generally show the curved and dull plane {103}; they are often twinned on (100).

Girgenti (Sicily).—Fine transparent crystals occur with the sulphur and celestite in the marl of this locality; they are usually twins, on

(100), and are often curved; the crystals sometimes have the face (100) developed. Here, and at Bex, twin crystals bearing the face (103), which is almost exactly perpendicular to the vertical axis, may present an unusual appearance, this form nearly coinciding in the two individuals and constituting a single curved surface. The gypsum of Girgenti and other localities sometimes encloses movable drops of water.

Montmartre (Paris).—The large honey-yellow crystals, found in the beds of gypsum which are interstratified with marls and clays, are almost always lenticular; they are also often twinned on (101), and the curvature of the crystals in these gives rise to the so-called "swallow-tail twins," which are especially conspicuous when bounded by cleavage faces B. In these twins it will be noticed that the conchoidal cleavage of one individual nearly coincides with the fibrous cleavage of the other.

The selenite of Montmartre is far less flexible and more brittle than that of most localities.

Fig. 665.—Gypsum twinned on (100).

Many other sulphates are found as minerals; of these some are too rare to be considered here, others are soluble in water and are only found as massive or fibrous deposits and incrustations in which the characters of the minerals can scarcely be studied. Among the latter, **chalcanthite** (*Fr.* cyanose), the common blue anorthic sulphate of copper, $CuSO_4 . 5H_2O$, and **melanterite**, the common green ferrous sulphate, $FeSO_4 . 7H_2O$, are common as decomposition products of copper and iron ores; melanterite in particular is the usual result of the decomposition of marcasite and pyrites, and makes its appearance as a pale green or nearly colourless efflorescence; it may be recognised by its astringent taste.

Epsomite (*Germ.* Bittersalz), $MgSO_4 . 7H_2O$, is not isomorphous with melanterite, but belongs to the sulphur class of the orthorhombic system; like chalcanthite and melanterite it is often abundant in mine waters, and it occurs in botryoidal crusts and fibrous efflorescences.

Among the **alums**, $R'Al(SO_4)_2 . 12H_2O$, potash-, soda- and ammonia-alums occur in nature; but these also are merely fibrous deposits in shales and clays.

Alunite, or alumstone, $K(AlO_2H_2)_3(SO_4)_2 . 3H_2O$, is a very different mineral, insoluble in water and possessing a hardness of 4. It is found in white, impure, massive deposits in volcanic rocks which have been

permeated by sulphurous vapours. In the neighbourhood of Rome and in Hungary it is burnt for the manufacture of alum; crystals are rare, but small rhombohedra may sometimes be observed in cavities.

The following may possibly be double salts :—

Glauberite, $Na_2SO_4 . CaSO_4$, found in well-developed monoclinic crystals at Stassfurt and in other salt mines.

Hanksite, $9Na_2SO_4 . 2Na_2CO_3 . KCl$, found in large hexagonal prisms and pyramids in the borax deposits of California.

There are also a number of basic sulphates, mostly hydrated, of copper and of iron.

CHROMATES

The chromates might be expected to be isomorphous with the sulphates; a calcium chromate isomorphous with gypsum has been produced artificially. The only chromate of any importance among minerals is **crocoite** (*Germ.* Rothbleierz), the lead chromate $PbCrO_4$, which is found in fine monoclinic crystals, but is not isomorphous with any known mineral sulphate. Crocoite is of a beautiful hyacinth-red (which loses its brilliancy on exposure to light), and adamantine lustre, with orange-yellow streak. Crystals of acute habit are found in quartz veins in the granite of Beresov in the Urals, and in Brazil. Long transparent prisms with oblique terminations have recently been found near Dundas in Tasmania.

Crocoite has been used as a paint and possesses the same composition as the artificial chrome yellow, which has the colour of the crocoite streak. It was in this mineral that the element chromium was discovered by Berzelius.

SECTION XXVII

THE TUNGSTATES, NIOBATES AND NITRATES

Of the remaining classes of minerals only a few species deserve brief mention, since they are either (tungstates and niobates) very rare, or (nitrates) soluble compounds which occur only in beds of massive material.

The Tungstates

THE SCHEELITE GROUP

Scheelite	$CaWO_4$
Wulfenite	$PbMoO_4$
Stolzite	$PbWO_4$
Cuprotungstite	$CuWO_4$
Powellite	$CaMoO_4$

Scheelite. — Tungstate of calcium; $CaWO_4$; $CaO = 19{\cdot}4$, $WO_3 = 80{\cdot}6$. Tetragonal; symmetry, tetragonal equatorial. $a : c = 1 : 1{\cdot}536$. Common form, bipyramids. Complementary twinning. Cleavage $\{111\}$, fair; $\{101\}$, imperfect. Brittle. Fracture, uneven. $H = 4\frac{1}{2}$; $G = 6$. White. Streak, white. Lustre, vitreous to adamantine. Translucent; $\omega = 1{\cdot}919$. Birefringence fairly strong, positive; $\epsilon - \omega = 0{\cdot}016$. Fusible (5) with difficulty. Decomposed by hydrochloric acid.

With the above description compare crystals from **Zinnwald** (Bohemia).

Wulfenite. — Molybdate of lead; $PbMoO_4$; $PbO = 60{\cdot}7$, $MoO_3 = 39{\cdot}3$. Tetragonal; symmetry, tetragonal polar. $a : c = 1 : 1{\cdot}577$. Common form, square tables. Cleavage $\{111\}$, fair. Brittle. Fracture, sub-conchoidal. $H = 3$; $G = 6{\cdot}7$. Red. Streak, white. Lustre, adamantine to resinous. Translucent; $\omega = 2{\cdot}402$. Birefringence, strong, negative; $\omega - \epsilon = 0{\cdot}098$. Easily fusible (2). Decomposed by hydrochloric acid.

With the above description compare crystals from **Yuma County** (Arizona).

Scheelite generally occurs in square bipyramids somewhat resembling octahedra (Fig. 131, p. 57), and the tetragonal (as opposed to ditetragonal) character of the symmetry is shown by the triangular faces which occur on only one corner of each octahedron face, or by striations corresponding to these. Supplementary twins may easily be mistaken for

simple crystals unless attention be paid to these striations, which in the twin meet at an angle on each octahedron face.

Scheelite is one of the minerals found associated with topaz, fluor, apatite, etc., in connection with the tin-bearing veins of certain granites.

Crystals of considerable size have been found under these conditions in the Bohemian and Saxon tin-mining region; also associated with molybdenite, apatite, gilbertite and lead ores at Carrock Fell, Cumberland, and in chlorite with wolframite at Tavistock in Devonshire.

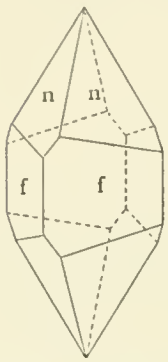

Fig. 666.—Wulfenite.

Tungstic acid was discovered in this mineral by the Swedish chemist Scheele, after whom it is named; the mineral had previously been called tungsten or heavy stone and regarded as an iron ore.

Wulfenite (*Germ.* Gelbbleierz) is found in brilliant red crystals, square plates with bevelled edges and very flat pyramid faces, in Arizona, and in thin pale yellow square plates in the lead mines of Carinthia. The tetragonal nature of the symmetry may sometimes be detected by the presence of pyramid faces like those of scheelite, but sometimes also by the faces of the prism (as shown in Fig. 666), which is tetragonal and not ditetragonal.

Crystals have recently been described, from New Mexico, which are pyramids somewhat resembling Fig. 666, with the exception that they are differently terminated at the two ends. This mineral is then certainly polar, but there is no evidence of such a polarity in scheelite, nor in stolzite, which is found in yellow bipyramids.

The minerals of this group enter into isomorphous mixture with each other to a small extent; scheelite contains some molybdate, wulfenite some lime. Cuprotungstite and powellite are very rare minerals.

WOLFRAMITE

Wolframite.—Tungstate of manganese and iron; $(Fe,Mn)WO_4$; $FeO = 19$ to 2, $MnO = 6$ to 22, $WO_3 = 76$. Monoclinic; holosymmetric. Cleavage {010}, perfect; {100}, imperfect. Brittle. Fracture, uneven. $H = 5\frac{1}{2}$; $G = 7{\cdot}3$. Black. Streak, dark reddish-brown. Lustre, metallic adamantine. Opaque. Fusible (3) to a magnetic bead. Decomposed by hydrochloric acid.

With the above description compare crystals from **Schlaggenwald** (Bohemia).

Wolframite occurs generally under the same conditions as scheelite in tin-bearing regions, and is often associated with that mineral; it is fairly common as a black mineral accompanying cassiterite in Cornwall and elsewhere, and is commercially of importance as a source of tungsten for use in the manufacture of tungsten steel.

It may generally be recognised by its lustre and the perfect single cleavage, which resembles that of stibnite. It approximates very closely in its angles to orthorhombic symmetry, and was long supposed to

belong to that system ; it is sometimes twinned on (100) and also on (023).

Wolframite bears no crystallographic relation to the scheelite group.

Two pure tungstates of iron have been described ; one (from Japan) is said to be tetragonal and isomorphous with scheelite, the other (the artificial $FeWO_4$) may be isomorphous with wolframite. An almost pure tungstate of manganese, containing only a small percentage of iron, is a mineral known as **hübnerite**, which has the same form as wolframite.

The tungstic acid of scheelite, stolzite, and wolframite is best detected by the yellow residue of tungstic oxide left after boiling with aqua regia ; the blowpipe reactions are masked by the presence of iron and manganese, especially in the case of wolframite. The molybdic acid of wulfenite may be detected by the permanent intense blue colour given by adding metallic zinc, after moistening with water the residue obtained by treatment with hydrochloric acid and evaporation ; the coloration obtained from wolframite fades on dilution.

THE NIOBATES AND TANTALATES

These are a rare group of minerals, of which many are found in the granitic rocks of Sweden ; they are chiefly of chemical interest as the sources of rare elements such as yttrium, erbium, cerium, thorium, lanthanum and didymium ; they are mostly black opaque minerals, imperfectly crystallised and difficult to distinguish.

The best crystallised and most widely distributed of the series is **columbite**, a niobate of iron and manganese $(Fe, Mn)Nb_2O_6$, in which a variable proportion of niobic is replaced by tantalic acid. This occurs in lustrous black opaque crystals of submetallic lustre belonging to the orthorhombic system. The specific gravity of all these minerals is high ; that of columbite is about 5·5.

It was in columbite that the element niobium was first discovered.

Brilliant crystals of columbite are found in the cryolite of West Greenland ; and among localities already mentioned for other minerals may be added Bodenmais in Bavaria, where columbite occurs in the granite with magnetite and cordierite, and the granite of the Ilmen Mountains in Siberia.

THE NITRATES

These are of immense commercial importance, and occur in large deposits in the dry districts of Chili, but being soluble in water they are found almost exclusively as massive or fibrous deposits or as incrustations. The only two nitrates of importance are :—

Nitre (saltpetre, salitre, *Germ.* Kalisalpeter), KNO_3.

Nitratine (chilisaltpetre, caliche, *Germ.* Natronsalpeter), $NaNO_3$.

Nitre is found in India as a white surface-deposit, and in many parts of the world as an efflorescence or crystalline crust mixed with porous soils.

Nitratine in Chili is associated with gypsum and salt; the "caliche," or impure nitrate, is sometimes of a vivid yellow or violet colour.

The crystallographic relationship between sodium nitrate and calcium carbonate has been pointed out on p. 238; crystals of the former are almost unknown in nature. Both nitre and nitratine are probably to a large extent of organic origin.

TABLES

General Survey of the Mineral Kingdom

The following list contains the most important and best known minerals, together with many which, though very rare, are inserted because they represent important classes or groups.

Within each class the minerals are arranged as follows :—

1. Salts containing monovalent elements . . . . . R′-salts
2. ,, ,, divalent elements (sometimes with monovalent) . . R″-salts
3. ,, ,, trivalent elements (sometimes with monovalent or divalent) R‴-salts
4. Miscellaneous (*i.e.* double salts, etc.)

A mineral group is placed in the division to which its simplest members may be referred, but it must be remembered that within a group one or more atoms may be replaced by an equal number of atoms having different valencies, provided that the total valency is the same. Thus the Pyroxene Group is $R''_2(SiO_3)_2$ if its simplest members, such as enstatite, $Mg_2(SiO_3)_2$, be taken as the type ; hence it belongs to the second of the above divisions. But the group may also contain members of the type $R'R'''(SiO_3)_2$, such as spodumene, $LiAl(SiO_3)_2$; these, if considered by themselves, should belong to division 3 ; but they cannot be separated from the Pyroxene Group, and the group, as a whole, is classed by its simplest type.

Again, within each group the formulæ quoted are the simplest possible, but it must be remembered that the analyses seldom represent so simple a composition, since any of the vicarious replacements mentioned above (OH for F, Mg″ for Ca″, Fe‴ for Al‴, etc.) may take place. Further, there may be isomorphous mixtures between the different members of a group ; where these are sufficiently well defined to receive special names they are incorporated in the group. It must be remembered also that in the silicates Al may often belong partly to the basic and partly to the acid radicle, H to the basic radicle or to water of crystallisation ; these are difficulties which make it impossible in the present state of our knowledge to draw up a satisfactory classification of minerals.

List of the Principal Minerals

Class I.—Elements

Metals—

The Copper Group	Gold	Au
	Silver	Ag
	Mercury	Hg
	Amalgam	(Ag,Hg)
	Copper	Cu
	Lead	Pb

Metals (*continued*)—

The Platinum Group	Iron	Fe
	Platinum	Pt
	Iridosmine	(Ir,Os)
The Arsenic Group	Arsenic	As
	Allemontite	(Sb,As)
	Antimony	Sb
	Bismuth	Bi

Metalloids—

	Sulphur	S
	Diamond	C
	Graphite	C

Class II.—Haloids

R′-haloids—

The Salt Group	Salt	NaCl
	Sylvite	KCl
	Sal-ammoniac	NH_4Cl
	Cerargyrite	AgCl
	Iodobromite	Ag(Cl,Br,I)
	Bromyrite	AgI
	Calomel	HgCl
	Iodyrite	AgI
	Marshite	CuI

R″-haloids—

Fluor	CaF_2
Sellaite	MgF_2
Cotunnite	$PbCl_2$
Bischofite	$MgCl_2 . 6H_2O$
Carnallite	$KCl . MgCl_2 . 6H_2O$

R‴-haloids—

Tysonite	$(Ce,La,Di)F_3$
Fluellite	$AlF_3 . H_2O$
Cryolite	$3NaF . AlF_3$
Chiolite	$5NaF . 3AlF_3$
Erythrosiderite	$2KCl . FeCl_3 . H_2O$
Pachnolite	$NaF . CaF_2 . AlF_3 . H_2O$
Thomsenolite	$NaF . CaF_2 . AlF_3 . H_2O$
Ralstonite	$2NaF . MgF_2 . 6Al(F,OH)_3 . 4H_2O$
Prosopite	$CaF_2 . 2Al(F,OH)_3$

Oxychlorides, etc.—

Penfieldite	$2PbCl_2 . PbO$
Matlockite	$PbCl_2 . PbO$
Mendipite	$PbCl_2 . 2PbO$
Schwartzembergite	$Pb(I,Cl)_2 . 2PbO$
Laurionite	$PbCl_2 . Pb(OH)_2$
Atacamite	$CuCl_2 . 3Cu(OH)_2$
Percylite	$PbCuCl_2(OH)_2$
Boleite	$3PbCuCl_2(OH)_2 . AgCl$

Class III.—Sulphides, Arsenides, etc.

R′-sulphides—

The Acanthite Group	Aeanthite	Ag_2S
	Stromeyerite	$(Cu, Ag)_2S$
	Copper-glance	Cu_2S

R′-sulphides (*continued*)—

The Argentite Group	Argentite	Ag_2S
	Hessite	Ag_2Te
	Petzite	$(Ag,Au)_2Te$

R″-sulphides—

The Galena Group	Galena	PbS
	Altaite	PbTe
	Clausthalite	PbSe
The Blende Group	Blende	ZnS
	Metacinnabarite	HgS
	Tiemannite	HgSe
	Pentlandite	(Fe,Ni)S
	Alabandite	MnS
The Wurtzite Group	Wurtzite	ZnS
	Greenockite	CdS
	Millerite	NiS
	Niccolite	NiAs
	Breithauptite	NiSb
The Cinnabar Group	Cinnabar	HgS
	Covellite	CuS
The Pyrites Group	Pyrites	FeS_2
	Hauerite	MnS_2
	Smaltite	$CoAs_2$
	Chloanthite	$NiAs_2$
	Cobaltite	CoAsS
	Gersdorffite	NiAsS
	Ullmannite	NiSbS
	Sperrylite	$PtAs_2$
	Laurite	RuS_2
The Marcasite Group	Marcasite	FeS_2
	Löllingite	$FeAs_2$
	Mispickel	FeAsS
	Glaucodote	(Co,Fe)AsS
	Safflorite	$CoAs_2$
	Rammelsbergite	$NiAs_2$

R‴-sulphides—

	Realgar	AsS
The Stibnite Group	Orpiment	As_2S_3
	Stibnite	Sb_2S_3
	Bismuthite	Bi_2S_3
	Guanajuatite	Bi_2Se_3

Miscellaneous Sulphides—

Dyscrasite	Ag_3Sb
Nagyagite	$(Pb,Au)_{16}Sb_3(S,Te)_{24}$
Sylvanite	$AuAgTe_4$
Polydymite	Ni_4S_5
Skutterudite	$CoAs_3$
Molybdenite	MoS_2
Tetradymite	Bi_2Te_2S
Calaverite	$AuTe_2$

Class IV.—Sulphur Salts

Sulphoferrites, etc.—

Pyrrhotite	$Fe_{11}S_{12}$
Erubescite	$3Cu_2S.Fe_2S_3$

Sulphoferrites, etc. (*continued*)—

	Linnæite	$CoS . Co_2S_3$
	Cubanite	$CuS . Fe_2S_3$
	Chalcopyrite	$Cu_2S . Fe_2S_3$
	Stannite	$Cu_2S . FeSnS_3$
	Sternbergite	$Ag_2S . Fe_4S_5$

Sulphostannates and Sulphogermanates—

	Argyrodite	$4Ag_2S . GeS_2$
	Canfieldite	$4Ag_2S(Sn,Ge)S_2$
	Cylindrite	$6PbS . 6SnS_2 . Sb_2S_3$
	Franckeite	$5PbS . 2SnS_2 . Sb_2S_3$

Sulphantimonites, Sulpharsenites, Sulphobismuthites—

The Polybasite Group	Polybasite	$9Ag_2S . Sb_2S_3$
	Pearceite	$9Ag_2S . As_2S_3$
The Stephanite Group	Stephanite	$5Ag_2S . Sb_2S_3$
	Geocronite	$5PbS . Sb_2S_3$
The Tetrahedrite Group	Tetrahedrite	$3Cu_2S . Sb_2S_3$
	Tennantite	$3Cu_2S . As_2S_3$
The Meneghinite Group	Meneghinite	$4PbS . Sb_2S_3$
	Jordanite	$4PbS . As_2S_3$
The Pyrargyrite Group	Pyrargyrite	$3Ag_2S . Sb_2S_3$
	Proustite	$3Ag_2S . As_2S_3$
The Pyrostilpnite Group	Pyrostilpnite	$3Ag_2S . Sb_2S_3$
	Xanthoconite	$3Ag_2S . As_2S_3$
The Bournonite Group	Bournonite	$2PbS . Cu_2S . Sb_2S_3$
	Aikinite	$2PbS . Cu_2S . Bi_2S_3$
	Boulangerite	$5PbS . 2Sb_2S_3$
	Freieslebenite	$5(Ag_2,Pb)S . 2Sb_2S_3$
	Diaphorite	$5(Ag_2,Pb)S . 2Sb_2S_3$
The Jamesonite Group	Jamesonite	$2PbS . Sb_2S_3$
	Dufrenoysite	$2PbS . As_2S_3$
	Plagionite	$5PbS . 4Sb_2S_3$
The Zinckenite Group	Zinckenite	$PbS . Sb_2S_3$
	Scleroclase	$PbS . As_2S_3$
	Emplectite	$Cu_2S . Bi_2S_3$
	Andorite	$2PbS . Ag_2S . 3Sb_2S_3$
	Wolfsbergite	$Cu_2S . Sb_2S_3$
The Miargyrite Group	Miargyrite	$Ag_2S . Sb_2S_3$
	Lorandite	$Tl_2S . As_2S_3$

Sulpharsenates, etc.—

The Famatinite Group	Famatinite	$3Cu_2S . Sb_2S_5$
	Enargite	$3Cu_2S . As_2S_5$

Oxysulphides—

Voltzite	Zn_5S_4O
Kermesite	Sb_2S_2O

Class V.—Oxides

R′-oxides—

Ice	H_2O
Cuprite	Cu_2O

R″-oxides—

Periclase	MgO
Zincite	ZnO

R″-oxides (*continued*)—

	Melaconite	CuO
The Brucite Group	Brucite	$MgO . H_2O$
	Pyrochroite	$MnO . H_2O$

R‴-oxides—

The Corundum Group	Corundum	Al_2O_3
	Hæmatite	Fe_2O_3
The Senarmontite Group	Senarmontite	Sb_2O_3
	Arsenolite	As_2O_3
The Valentinite Group	Valentinite	Sb_2O_3
	Claudetite	As_2O_3
The Göthite Group	Göthite	$Fe_2O_3 . H_2O$
	Diaspore	$Al_2O_3 . H_2O$
	Manganite	$Mn_2O_3 . H_2O$
	Limonite	$2Fe_2O_3 . 3H_2O$
	Xanthosiderite	$Fe_2O_3 . 2H_2O$
	Bauxite	$Al_2O_3 . 2H_2O$
	Gibbsite	$Al_2O_3 . 3H_2O$
	Sassolite	$B_2O_3 . 3H_2O$

R^{IV}-oxides—

	Tellurite	TeO_2
The Cassiterite Group	Cassiterite	SnO_2
	Polianite	MnO_2
	Rutile	TiO_2
	Plattnerite	PbO_2
	Anatase	TiO_2
	Brookite	TiO_2
	Pyrolusite	MnO_2
	Baddeleyite	ZrO_2
	Quartz	SiO_2
	Tridymite	SiO_2
	Chalcedony	SiO_2
	Opal	$SiO_2 . xH_2O$
	Melanophlogite	$SiO_2 . xH_2O . ySO_3$

Class VI.—Manganites

Hausmannite	$2MnO . MnO_2$
Braunite	$MnO . MnO_2$
Psilomelane	$xMnO . yBaO . zMnO_2 . H_2O$
Chalcophanite	$(Mn,Zn)O . 2MnO_2 . 2H_2O$
Bixbyite	$FeO . MnO_2$

Class VII.—Aluminates

The Spinel Group	Spinel	$MgAl_2O_4$
	Hercynite	$FeAl_2O_4$
	Gahnite	$ZnAl_2O_4$
	Jacobsite	$(Mn,Mg)(Fe,Mn)_2O_4$
	Franklinite	$(Fe,Zn,Mn)(Fe,Mn)_2O_4$
	Magnetite	$FeFe_2O_4$
	Magnesioferrite	$MgFe_2O_4$
	Chromite	$FeCr_2O_4$
	Chrysoberyl	$BeAl_2O_4$

Class VIII.—Borates

R′-borates—

Larderellite	$(NH_4)_2B_8O_{13}.4H_2O$
Borax	$Na_2B_4O_7.10H_2O$

R″-borates—

Pinnoite	$MgB_2O_4.3H_2O$
Colemanite	$Ca_2B_6O_{11}.5H_2O$
Sussexite	$H(Mn,Mg,Zn)BO_3$
Hambergite	$Be_2(OH)BO_3$
Ulexite	$NaCaB_5O_9.8H_2O$

R‴-borates—

Jeremejevite	$AlBO_3$
Rhodizite	$KAl_2B_3O_8$

Miscellaneous borates—

Pinakiolite	$Mg_3(BO_3)_2.Mn_2MnO_4$
Ludwigite	$Mg_3(BO_3)_2.Fe_2FeO_4$
Nordenskiöldine	$CaSnB_2O_6$
Boracite	$Mg_7Cl_2B_{16}O_{30}$
Sulphoborite	$4HMgBO_3.2MgSO_4.7H_2O$
Heintzite	$KMg_2B_{11}O_{19}.7H_2O$

Class IX.—Carbonates

R′-carbonates—

Teschemacherite	$H(NH_4)CO_3$
Thermonatrite	$Na_2CO_3.H_2O$
Trona	$HNa_3(CO_3)_2.2H_2O$
Natron	$Na_2CO_3.10H_2O$

R″-carbonates—

The Calcite Group

Calcite	$CaCO_3$
Dolomite	$CaCO_3.MgCO_3$
Magnesite	$MgCO_3$
Ankerite	$Ca(Mg,Fe)(CO_3)_2$
Mesitite	$Mg_2Fe(CO_3)_3$
Chalybite	$FeCO_3$
Rhodochrosite	$MnCO_3$
Sphærocobaltite	$CoCO_3$
Calamine	$ZnCO_3$

The Aragonite Group

Aragonite	$CaCO_3$
Bromlite	$(Ca,Ba)CO_3$
Witherite	$BaCO_3$
Strontianite	$SrCO_3$
Cerussite	$PbCO_3$

Barytocalcite	$CaCO_3.BaCO_3$
Malachite	$(CuOH)_2CO_3$
Chessylite	$Cu(CuOH)_2(CO_3)_2$
Aurichalcite	$2(Zn,Cu)CO_3.3(Zn,Cu)(OH)_2$
Pirssonite	$CaCO_3.Na_2CO_3.2H_2O$
Gaylussite	$Na_2CO_3.CaCO_3.5H_2O$

R‴-carbonates—

Lanthanite	$La_2(CO_3)_3.9H_2O$
Dawsonite	$NaAl(OH)_2CO_3$

Miscellaneous carbonates—

	Bastnäsite	$(Ce, La, Di)FCO_3$
The Parisite Group	Parisite	$(CeF)_2Ca(CO_3)_3$
	Cordylite	$(CeF)_2Ba(CO_3)_3$
	Phosgenite	$(PbCl)_2CO_3$
	Northupite	$MgCO_3 . Na_2CO_3 . NaCl$

Class X.—Silicates and Titanates

R″-silicates—

The Phenacite Group	Phenacite	Be_2SiO_4
	Dioptase	H_2CuSiO_4
	Willemite	Zn_2SiO_4
	Trimerite	$MnBeSiO_4$
The Olivine Group	Monticellite	$CaMgSiO_4$
	Forsterite	Mg_2SiO_4
	Olivine	$(Mg, Fe)_2SiO_4$
	Fayalite	Fe_2SiO_4
	Knebelite	$(Fe, Mn)_2SiO_4$
	Roepperite	$(Fe, Mn, Zn)_2SiO_4$
	Tephroite	Mn_2SiO_4
The Chondrodite Group	Chondrodite	$Mg_3(MgF)_2(SiO_4)_2$
	Humite	$Mg_5(MgF)_2(SiO_4)_3$
	Clinohumite	$Mg_7(MgF)_2(SiO_4)_4$
The Pyroxene Group	Enstatite	$MgSiO_3$
	Hypersthene	$(Mg, Fe)SiO_3$
	Diopside	$MgCa(SiO_3)_2$
	Hedenbergite	$FeCa(SiO_3)_2$
	Augite	$CaMg(SiO_3)_2$, $MgAl_2SiO_6$
	Jeffersonite	$(Ca, Mn)(Mg, Fe, Zn)(SiO_3)_2$
	Schefferite	$(Ca, Mn)(Mg, Fe)(SiO_3)_2$
	Acmite	$NaFe'''(SiO_3)_2$
	Spodumene	$LiAl(SiO_3)_2$
	Jadeite	$NaAl(SiO_3)_2$
	Wollastonite	$CaSiO_3$
	Pectolite	$HNaCa_2(SiO_3)_3$
	Rhodonite	$MnSiO_3$
	Babingtonite	$Ca_2Fe(SiO_3)_3$, $Fe_2(SiO_3)_3$
The Amphibole Group	Anthophyllite	$MgSiO_3$
	Tremolite	$CaMg_3(SiO_3)_4$
	Actinolite	$Ca(Mg, Fe)_3(SiO_3)_4$
	Hornblende	$Ca(Mg, Fe)_3(SiO_3)_4$, $CaMg_2Al_2(SiO_4)_3$
	Glaucophane	$NaAl(SiO_3)_2 . MgSiO_3$
	Riebeckite	$NaFe'''(SiO_3)_2 . FeSiO_3$
	Ænigmatite	$Na_4Fe_9AlFe'''(Si, Ti)_{12}O_{38}$
The Ilmenite Group	Ilmenite	$FeTiO_3$
	Geikielite	$MgTiO_3$
	Pyrophanite	$MnTiO_3$
	Perovskite	$CaTiO_3$
	Titanite	$CaTiSiO_5$
	Keilhauite	$CaTiSiO_5$, $(Al, Fe, Y)_2SiO_5$

R″-silicates (*continued*)—

Kentrolite	$Pb_3Mn_4Si_3O_{15}$
Melanotekite	$Pb_3Fe'''_4Si_3O_{15}$
Barysilite	$Pb_3Si_2O_7$
Hemimorphite	$(ZnOH)_2SiO_3$
Clinohedrite	$(ZnOH)(CaOH)SiO_3$
Chrysocolla	$CuSiO_3 . 2H_2O$
Talc	$H_2Mg_3(SiO_3)_4$
Serpentine	$H_4Mg_3Si_2O_9$
Bertrandite	$H_2Be_4Si_2O_9$
Bementite	$2MnSiO_3 . H_2O$
Inesite	$2(Mn,Ca)SiO_3 . H_2O$
Deweylite	$H_4Mg_2Ni_2(SiO_4)_3 . 4H_2O$
Gyrolite	$H_2Ca_2(SiO_3)_3 . H_2O$
Okenite	$H_2Ca(SiO_3)_2 . H_2O$
Apophyllite	$(H,K)_2Ca(SiO_3)_2 . H_2O$
Leucophane	$NaCaBeF(SiO_3)_2$
Eudidymite	$HNaBeSi_3O_8$
Epididymite	$HNaBeSi_3O_8$

R‴-silicates—

Topaz	$(AlF)_2SiO_4$
Andalusite	$Al(AlO)SiO_4$
Cyanite	$(AlO)_2SiO_3$
Sillimanite	Al_2SiO_5
Kaolinite	$H_4Al_2Si_2O_9$
Pyrophyllite	$H_2Al_2(SiO_3)_4$
Allophane	$Al_2SiO_5 . 5H_2O$
Dumortierite	$Al_8Si_3O_{18}$
Zunyite	$Al_3(OH,F,Cl)_{12}(SiO_4)_3$
Eulytite	$Bi_4(SiO_4)_3$
Agricolite	$Bi_4(SiO_4)_3$
Pseudobrookite	$Fe'''_4(TiO_4)_3$
Kaliophilite	$KAlSiO_4$
Leucite	$KAl(SiO_3)_2$
Petalite	$LiAl(Si_2O_5)_2$
Pollucite	$H_2Cs_4Al_4(SiO_3)_9$
Nepheline	$K_2Na_6Al_8Si_9O_{34}$
The Sodalite Group	
Sodalite	$Na_4(AlCl)Al_2(SiO_4)_3$
Haüyne	$Na_2Ca(NaSO_4Al)Al_2(SiO_4)_3$
Nosean	$Na_4(NaSO_4Al)Al_2(SiO_4)_3$
Lazurite	$Na_4(NaS_3Al)Al_2(SiO_4)_3$
Cerite	$H_6Ce_4Si_3O_{15}$
The Felspar Group	
Orthoclase	$KAlSi_3O_8$
Hyalophane	$2KAlSi_3O_8 . BaAl_2Si_2O_8$
Anorthoclase	$(Na,K)AlSi_3O_8$
Microcline	$KAlSi_3O_8$
Albite	$NaAlSi_3O_8 ... = Ab$
Oligoclase	Ab_3An_1
Andesine	Ab_1An_1
Labradorite	Ab_1An_3
Anorthite	$CaAl_2Si_2O_8 ... = An$
The Mica Group	
Muscovite	$H_2KAl_3(SiO_4)_3$
Paragonite	$H_2NaAl_3(SiO_4)_3$

R‴-silicates (*continued*)—

The Mica Group (*continued*)		Phlogopite	$(K,H,MgF)_3Mg_3Al(SiO_4)_3$
		Biotite	$(K,H)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$
		Zinnwaldite	$(K,Li)_3Fe(AlF_2)Al_2(Si_3O_8)(SiO_4)_2$
		Lepidolite	$K_4Li_4H(AlF_2)_3Al_4(Si_3O_8)_3(SiO_4)_3$
		Tourmaline	$(Na_6,Mg_3,Al_2)_3(Al,Fe)_6(BOH)_4Si_6O_{38}$
The Scapolite Group		Meionite	$Ca_4Al_6Si_6O_{25}$
		Scapolite	$Ca_4Al_6Si_6O_{25}$ / $Na_4Al_3Si_9O_{24}Cl$
		Marialite	$Na_4Al_3Si_9O_{24}Cl$
		Sareolite	$Na_2Ca_8Al_6(SiO_4)_9$
The Melilite Group		Melilite	$Na_2Ca_{11}Al_4(SiO_4)_9$
		Gehlenite	$Ca_3Al_2Si_2O_{10}$
The Zeolites	The Heulandite Group	Heulandite	$H_4CaAl_2(SiO_3)_6 . 3H_2O$
		Brewsterite	$H_4(Sr,Ba,Ca)Al_2(SiO_3)_6 . 3H_2O$
		Epistilbite	$H_4CaAl_2(SiO_3)_6 . 3H_2O$
	The Stilbite Group	Wellsite	$(Ba,Ca,K_2)Al_2Si_3O_{10} . 3H_2O$
		Phillipsite	$K_2CaAl_2(SiO_3)_4 . 4H_2O$
		Harmotome	$(K_2,Ba)Al_2Si_5O_{15} . 5H_2O$
		Stilbite	$(Na_2,Ca)Al_2Si_6O_{16} . 6H_2O$
		Gismondite	$CaAl_2(SiO_3)_4 . 4H_2O$
		Laumontite	$H_4CaAl_2Si_4O_{14} . 2H_2O$
	The Chabazite Group	Chabazite	$CaAl_2(SiO_3)_4 . 6H_2O$
		Gmelinite	$Na_2Al_2(SiO_3)_4 . 6H_2O$
		Analeite	$NaAl(SiO_3)_2 . H_2O$
	The Natrolite Group	Natrolite	$Na_2Al_2Si_3O_{10} . 2H_2O$
		Mesolite	$Na_2Al_2Si_3O_{10} . 2H_2O$ / $CaAl_2Si_3O_{10} . 3H_2O$
		Scolecite	$CaAl_2Si_3O_{10} . 3H_2O$
		Edingtonite	$BaAl_2Si_3O_{10} . 3H_2O$
		Thomsonite	$2(Na_2,Ca)Al_2(SiO_4)_2 . 5H_2O$
		Milarite	$HKCa_2Al_2(Si_2O_5)_6$
The Epidote Group		Epidote	$Ca_2Al_2(AlOH)(SiO_4)_3$ / $Ca_2Fe_2(FeOH)(SiO_4)_3$
		Zoisite	$Ca_2Al_2(AlOH)(SiO_4)_3$
		Allanite	$(Ca,Fe)_2(Al,Ce,Fe)_2(AlOH)(SiO_4)_3$
		Clinozoisite	$Ca_2Al_2(AlOH)(SiO_4)_3$
		Prehnite	$H_2Ca_2Al_2(SiO_4)_3$
		Lawsonite	$H_4CaAl_2Si_2O_{10}$
		Carpholite	$H_4MnAl_2Si_2O_{10}$
		Euclase	$HBeAlSiO_5$
		Axinite	$H(Ca,Fe)_3Al_2B(SiO_4)_4$
		Homilite	$(Ca,Fe)_3B_2Si_2O_{10}$
		Datolite	$CaB_2(SiO_4)_2$
		Vesuvianite	$H_2Ca_6(Al,Fe)_3Si_5O_{18}$
		Ilvaite	$CaFe_2(FeOH)(SiO_4)_2$
		Staurolite	$Fe(AlO)_4(AlOH)(SiO_4)_2$
		Margarite	$H_2CaAl_4Si_2O_{12}$
		Chloritoid	$H_2(Fe,Mg)Al_2SiO_7$
		Clinochlore	$H_8(Mg,Fe)_5Al_2Si_3O_{18}$
		Pennine	$H_8(Mg,Fe)_5Al_2Si_3O_{18}$
		Clintonite	$H_3(Mg,Ca)_5Al_5Si_2O_{18}$

R‴-silicates (*continued*)—

	Cronstedtite	$H_8Fe''_4Fe'''_4Si_3O_{18}$
	Guarinite	$Na_2Ca_4(Al,Ce)_5Si_5O_{22}$
	Beryl	$Be_3Al_2(SiO_3)_6$
	Cordierite	$(Mg,Fe)_4Al_4Si_5O_{18}$
	Danburite	$CaB_2(SiO_4)_2$
	Gadolinite	$Be_2Fe(YO)_2(SiO_4)_2$
The Garnet Group	Grossular	$Ca_3Al_2(SiO_4)_3$
	Pyrope	$Mg_3Al_2(SiO_4)_3$
	Spessartite	$Mn_3Al_2(SiO_4)_3$
	Almandine	$Fe_3Al_2(SiO_4)_3$
	Uvarovite	$Ca_3Cr_2(SiO_4)_3$
	Andradite	$Ca_3Fe_2(SiO_4)_3$
	Kornerupine	$MgAl_2SiO_6$
	Sapphirine	$Mg_5Al_{12}Si_2O_{27}$

R^{iv}-silicates—

The Zircon Group	Zircon	$ZrSiO_4$
	Thorite	$ThSiO_4$
	Eudialyte	$Na_4(Ca,Fe)_3Zr(SiO_3)_7$
	Astrophyllite	$(Na,K)_4(Fe,Mn)_4Ti(SiO_4)_4$
	Catapleiite	$H_4Na_2ZrSi_3O_{11}$
	Elpidite	$H_6Na_2Zr(SiO_3)_6$
	Neptunite	$(Na,K)_2(Fe,Mn)Ti(SiO_3)_4$

Miscellaneous silicates—

The Helvite Group	Helvite	$(Mn,Fe)_2(Mn_2S)Be_3(SiO_4)_3$
	Danalite	$(Zn,Fe)_2(Fe_2S)Be_3(SiO_4)_3$
	Canerinite	$H_6Na_6Ca(NaCO_3)_2Al_8(SiO_4)_9$
	Thaumasite	$CaSiO_3 . CaCO_3 . CaSO_4 . 15H_2O$
	Pyrosmalite	$H_7(MnCl)(Fe,Mn)_4(SiO_4)_4$
	Friedelite	$H_7(MnCl)Mn_4(SiO_4)_4$
	Langbanite	$37Mn_5SiO_7 . 10Fe_3Sb_2O_8$
	Dysanalyte	$6(Ca,Fe)TiO_3 . (Ca,Fe)Nb_2O_6$

Class XI.—Nitrates

	Nitratine	$NaNO_3$
	Nitre	KNO_3
	Darapskite	$NaNO_3 . Na_2SO_4 . H_2O$
	Gerhardtite	$Cu_2(OH)_3NO_3$

Class XII.—Phosphates, Arsenates, etc.

R′-phosphates—

	Stercorite	$H(NH_4)NaPO_4 . 4H_2O$

R″-phosphates—

	Brandtite	$Ca_2Mn(AsO_4)_2$
	Fairfieldite	$Ca_2Mn(PO_4)_2$
	Hureaulite	$H_2Mn_5(PO_4)_4 . 4H_2O$
	Haidingerite	$HCaAsO_4 . H_2O$
The Pharmacolite Group	Pharmacolite	$HCaAsO_4 . 2H_2O$
	Brushite	$HCaPO_4 . 2H_2O$
	Newberyite	$HMgPO_4 . 3H_2O$
	Berzeliite	$(Ca,Mg,Mn)_3(AsO_4)_2$
	Roselite	$(Ca,Co)_3(AsO_4)_2 . 2H_2O$

R″-phosphates (*continued*)—

The Vivianite Group	Vivianite	$Fe_3(PO_4)_2 . 8H_2O$
	Symplesite	$Fe_3(AsO_4)_2 . 8H_2O$
	Erythrite	$Co_3(AsO_4)_2 . 8H_2O$
	Annabergite	$Ni_3(AsO_4)_2 . 8H_2O$
The Olivenite Group	Libethenite	$Cu_2(OH)PO_4$
	Olivenite	$Cu_2(OH)AsO_4$
	Adamite	$Zn_2(OH)AsO_4$
	Descloizite	$(Pb,Zn)_2(OH)VO_4$
	Herderite	$CaBe(F,OH)PO_4$
The Wagnerite Group	Wagnerite	$Mg(MgF)PO_4$
	Triplite	$(Fe,Mn)(MnF)PO_4$
	Triploidite	$(Mn,Fe)(MnOH)PO_4$
	Sarcinite	$Mn(MnOH)AsO_4$
	Adelite	$Ca(MgOH)AsO_4$
	Tilasite	$Ca(MgF)AsO_4$
	Clinoclase	$(CuOH)_3AsO_4$
The Apatite Group	Apatite	$Ca_4(CaF)(PO_4)_3$
	Svabite	$Ca_4Ca(F,OH)(AsO_4)_3$
	Pyromorphite	$Pb_4(PbCl)(PO_4)_3$
	Mimetite	$Pb_4(PbCl)(AsO_4)_3$
	Vanadinite	$Pb_4(PbCl)(VO_4)_3$
	Allactite	$Mn_7(OH)_8(AsO_4)_2$
	Euchroite	$Cu(CuOH)AsO_4 . 3H_2O$
	Cornwallite	$Cu(CuOH)_4(AsO_4)_2 . H_2O$
	Tyrolite	$Cu(CuOH)_4(AsO_4)_2 . 7H_2O$
	Dahllite	$4Ca_3(PO_4)_2 . 2CaCO_3 . H_2O$
	Beryllonite	$NaBePO_4$
	Struvite	$(NH_4)MgPO_4 . 6H_2O$

R‴-phosphates—

Pucherite	$BiVO_4$
Xenotime	YPO_4
Monazite	$(Ce,La,Di)PO_4$
Rhabdophane	$(La,Di,Y)PO_4 . H_2O$
Churchite	$CePO_4 . 4H_2O$
Scorodite	$Fe'''AsO_4 . 2H_2O$
Strengite	$Fe'''PO_4 . 2H_2O$
Variscite	$AlPO_4 . 2H_2O$
Augelite	$Al_2(OH)_3PO_4$
Dufrenite	$Fe'''_2(OH)_3PO$
Turquoise	$Al_2(OH)_4HPO_4$
Wavellite	$2Al_3(OH)_3(PO_4)_2 . 9H_2O$
Cacoxenite	$2Fe'''_2(OH)_3PO_4 . 9H_2O$
Pharmacosiderite	$2Fe'''AsO_4 . Fe'''(OK)_3 . 5H_2O$
Ludlamite	$Fe'''_7(OH)_2(PO_4)_4 . 8H_2O$
Mixite	$Cu_{10}Bi(OH)_8(AsO_4)_5 . 7H_2O$
Evansite	$Al_3(OH)_6PO_4 . 6H_2O$
Amblygonite	$Li(AlF)PO_4$
Durangite	$Na(AlF)AsO_4$

The Triphylite Group	Triphylite	$Li(Fe,Mn)PO_4$
	Lithiophilite	$Li(Mn,Fe)PO_4$
	Natrophilite	$NaMnPO_4$
	Lazulite	$(Fe,Mg)Al_2(OH)(PO_4)$

R‴-phosphates (*continued*)—

	Arseniosiderite	$Ca_3Fe'''_4(OH)_9(AsO_4)_3$
	Synadelphite	$Mn_5Al_2(OH)_{10}(AsO_4)_2$
	Hæmatolite	$Mn_4Al(OH)_8AsO_4$
	Flinkite	$Mn''_2Mn'''(OH)_4AsO_4$
	Hamlinite	$Al_3Sr(OH)_7P_2O_7$
	Florencite	$CeAl_3(OH)_6(PO_4)_2$
	Liroconite	$Cu_9Al_4(OH)_{15}(AsO_4)_5 . 20H_2O$
The Childrenite Group	Childrenite	$Fe''Al(OH)_2PO_4 . 2H_2O$
	Eosphorite	$MnAl(OH)_2PO_4 . 2H_2O$
	Chalcosiderite	$CuFe'''_2(Fe'''O)_4(PO_4)_4 . 8H_2O$
The Torbernite Group	Torbernite	$Cu(UO_2)_2(PO_4)_2 . 8H_2O$
	Zeunerite	$Cu(UO_2)_2(AsO_4)_2 . 8H_2O$
	Uranocircite	$Ba(UO_2)_2(PO_4)_2 . 8H_2O$
	Autunite	$Ca(UO_2)_2(PO_4)_2 . 8H_2O$
	Walpurgite	$Bi_{10}(UO_2)_3(OH)_{24}(AsO_4)_4$

Miscellaneous phosphates—

Lüneburgite	$H_2Mg_3(BO_2)_2(PO_4)_2 . 7H_2O$
Beudantite	$3PbSO_4 . 2FePO_4 . 6Fe(OH)_3$
Chalcophyllite	Hydr. arsenate and sulphate of Cu.

Antimonates—

Romeite	$CaSb_2O_4$
Atopite	$Ca_2Sb_2O_7$
Tripuhyite	$Fe_2Sb_2O_7$
Mauzeliite	$4(Ca,Pb)O . 2Sb_2O_5 . TiO_2 . F$
Lewisite	$5CaO . 3Sb_2O_5 . 2TiO_2$
Derbylite	$Fe''Sb_2O_6 . 3Fe'''TiO_3$
Nadorite	$(PbCl)SbO_2$

Class XIII.—Niobates, Tantalates, etc.

	Microlite	$Ca_2Ta_2O_7$
	Columbite	$(Fe,Mn)Nb_2O_6$
	Tantalite	$FeTa_2O_6$
	Tapiolite	$Fe(Nb,Ta)_2O_6$
	Samarskite	$(Fe,Ca,YO_2)_3(Y,Er,Ce)_2(Nb,Ta)_6O_{21}$
	Æschynite	$(Ce,La,Er)_2Nb_4O_{13} . (Ce,La,Er)_2(Ti,Th)_5O_{13}$
	Fergusonite	$(Y,Er,Ce)(Nb,Ta)O_4$
	Koppite	Niobates and titanates of Ce, Y, Er, etc.
	Polycrase	
	Euxenite	
	Pyrochlore	

Class XIV.—Sulphates

R′-sulphates—

Misenite	$HKSO_4$
Mascagnite	$(NH_4)_2SO_4$
Thenardite	Na_2SO_4
Aphthitalite	$(K,Na)_2SO_4$
Mirabilite	$Na_2SO_4 . 10H_2O$

R″-sulphates—

The Barytes Group	Barytes	$BaSO_4$
	Celestite	$SrSO_4$
	Anglesite	$PbSO_4$

R″-sulphates (*continued*)—

Anhydrite	$CaSO_4$
Kieserite	$MgSO_4 . H_2O$
Gypsum	$CaSO_4 . 2H_2O$
Chalcanthite	$CuSO_4 . 5H_2O$
Epsomite	$MgSO_4 . 7H_2O$
Goslarite	$ZnSO_4 . 7H_2O$
Melanterite	$FeSO_4 . 7H_2O$
Bieberite	$CoSO_4 . 7H_2O$
Brochantite	$Cu_4(OH)_6SO_4$
Caledonite	$(Pb,Cu)_2(OH)_2SO_4$
Linarite	$PbCu(OH)_2SO_4$
Lanarkite	$(Pb_2O)SO_4$
Langite	$Cu_4(OH)_6SO_4 . H_2O$
Leadhillite	$PbSO_4 . 2PbCO_3 . Pb(OH)_2$
Glauberite	$Na_2Ca(SO_4)_2$
Langbeinite	$K_2Mg_2(SO_4)_3$
Syngenite	$K_2Ca(SO_4)_2 . H_2O$
Blödite	$Na_2Mg(SO_4)_2 . 4H_2O$
Pieromerite	$K_2Mg(SO_4)_2 . 6H_2O$
Polyhalite	$K_2Ca_2Mg(SO_4)_4 . 2H_2O$

R‴-sulphates—

Alunogen	$Al_2(SO_4)_3 . 18H_2O$
Coquimbite	$Fe_2(SO_4)_3 . 9H_2O$
Aluminite	$(AlO)_2SO_4 . 9H_2O$
Carphosiderite	$Fe'''(Fe'''O)_5(SO_4)_4 . 10H_2O$
Amarantite	$Fe'''(Fe'''O)(SO_4)_2 . 7H_2O$
Utahite	$3(Fe'''O)_2SO_4 . 4H_2O$
Copiapite	$Fe'''_3(Fe'''O)(SO_4)_5 . 18H_2O$
Castanite	$Fe'''(Fe'''O)(SO_4)_2 . 8H_2O$
Alumian	$Al(AlO)(SO_4)_2$
Ferronatrite	$Na_3Fe'''(SO_4)_3 . 3H_2O$
Alunite	$K(AlO_2H_2)_3(SO_4)_2 . 3H_2O$
Jarosite	$K(Fe'''O_2H_2)_3(SO_4)_2 . 3H_2O$
Sideronatrite	$Na_4Fe'''_2S_4O_{17} . 7H_2O$
Kalinite	$KAl(SO_4)_2 . 12H_2O$
Tschermigite	$(NH_4)Al(SO_4)_2 . 12H_2O$
Pickeringite	$MgAl_2(SO_4)_4 . 22H_2O$
Halotrichite	$Fe'''Al_2(SO_4)_4 . 24H_2O$
Römerite	$Fe''Fe'''_2(SO_4)_4 . 12H_2O$
Botryogen	$Mg(Fe'''OH)(SO_4)_2 . 7H_2O$

Miscellaneous Sulphates—

Spangolite	$(AlCl)Cu_6(OH)_{12}SO_4 . 3H_2O$
Connellite	$Cu_{15}(Cl,OH)_4SO_{16} . 15H_2O$
Caraeolite	$Na_2SO_4 . Pb(OH)Cl$
Kainite	$MgSO_4 . KCl . 3H_2O$
Sulphohalite	$2Na_2SO_4 . NaCl . NaF$
Hanksite	$9Na_2SO_4 . 2Na_2CO_3 . KCl$
Johannite	Sulphate of uranium

Class XV.—Tellurates, etc.

Montanite	$Bi_2(OH)_4TeO_4$
Chalcomenite	$CuSeO_3 . 2H_2O$

Class XVI.—Chromates

Crocoite	$PbCrO_4$
Phœnicochroite	$Pb(Pb_2O)(CrO_4)_2$
Vauquelinite	$2(Pb, Cu)CrO_4 . (Pb, Cu)_3(PO_4)_2$

Class XVII.—Molybdates, Tungstates, etc.

The Scheelite Group	Wulfenite	$PbMoO_4$
	Powellite	$Ca(Mo, W)O_4$
	Stolzite	$PbWO_4$
	Cuprotungstite	$CuWO_4$
	Scheelite	$CaWO_4$
	Hübnerite	$MnWO_4$
	Raspite	$PbWO_4$
	Wolframite	$(Fe,Mn)WO_4$

Class XVIII.—Uranates

Uraninite	uranate of lead

Tables of Reactions

TABLE A

Colour imparted to Flame

1. Yellow	Sodium	given by even the minutest traces.
2. Reddish-yellow	Calcium	not easily obtained in many minerals.
3. Pale violet	Potassium	easily masked by sodium, unless observed through blue glass.
4. Crimson	Lithium	not given by many minerals besides Lepidolite, Spodumene, Petalite, Tourmaline.
5. Carmine	Strontium	(the silicates do not show it.) Not given by many minerals besides Celestite, Strontianite.
6. Emerald-green	Copper	blue if the mineral be moistened with HCl.
7. Bluish-green	Phosphorus	(phosphates); especially if the mineral be moistened with sulphuric acid.
8. Yellowish-green	Boron	(borates or borosilicates); the mineral is to be mixed with fluor and potassium bisulphate. A somewhat similar colour is given by carbonate and sulphate of barium and by oxide or sulphide of molybdenum.

TABLE B

Sublimates in Closed Tube

1. Water; given by all hydrated salts and those which contain hydroxyl; sometimes acid.
2. Metallic liquid globules of Mercury; given by most minerals containing mercury, if previously mixed with sodium carbonate.
3. Yellow drops of Sulphur; given by sulphides of arsenic and mercury, and in a less degree by some of the other sulphides.

4. Metallic mirror of Arsenic ; given by arsenic and many arsenides, arsenosulphides, etc. : when the bottom of the tube is broken and the mirror heated it is re-deposited as a white sublimate of As_2O_3, and an odour of garlic is noticeable.
5. Reddish sublimate of Antimony Oxy-sulphide ; given by sulphide of antimony and many sulphantimonites.
6. Yellow and red sublimates of Arsenic Sulphide ; given by sulphides of arsenic and many of the sulpharsenites.
7. Black (changing to red when rubbed) sublimate of Mercury Sulphide ; given by minerals containing sulphur and mercury.
8. White (or colourless) globules of Tellurium Oxide ; given by some minerals containing tellurium.

TABLE C

Sublimates in Open Tube

1. White crystalline (octahedra), As_2O_3 ; given by arsenic, arsenic sulphides, arsenides, arsenosulphides and sulpharsenites.
2. White amorphous infusible Antimony Oxides ; given by most minerals containing antimony ; often accompanied by white volatile crystalline oxide of antimony.
3. White or grayish metallic Tellurium Oxide, which may be fused to clear drops ; given by most minerals containing tellurium (tellurides).
4. White volatile crystalline Selenium Oxide ; given by many minerals containing selenium (selenides), often accompanied by metallic selenium.
5. Brown (changing to yellow when cold) fusible Bismuth Oxide ; given by most minerals containing bismuth (sulphobismuthites).
6. Pale yellow (changing to white when cold) crystalline network of Molybdenum Oxide ; given by oxide and sulphide of molybdenum.

TABLE D

Vapours in Open Tube

1. Acid fumes with a pungent sulphurous odour indicate Sulphur.
2. White fumes with a strong garlic odour indicate Arsenic.
3. Dense white fumes indicate Antimony.
4. Fumes having a strong horse-radish odour indicate Selenium (selenides).

TABLE E

Encrustations on Charcoal

1. White, distant from the assay, readily volatilised, giving a garlic odour, indicates Arsenic (arsenates, arsenides, etc.).
2. White, near the assay, volatile—Antimony (antimonides and sulphantimonites). A very similar encrustation is sometimes given by Lead.
3. Yellow while hot, white on cooling ; not volatilised—Zinc. Moistened with cobalt nitrate and ignited becomes green.
4. Faint yellow while hot, white on cooling ; not volatilised—Tin (not given by many minerals besides Cassiterite, Stannite). Moistened with cobalt nitrate and ignited becomes bluish-green.
5. Yellow ; disappears in the reducing flame—Lead.
6. Dark yellow, fainter on cooling ; disappears in the reducing flame– Bismuth (sulphobismuthites).
7. Reddish-brown, volatile—Cadmium (not given by many minerals besides Greenockite).
8. Red—Silver, in presence of lead and antimony.

Whitish encrustations are also given by Se, Tl, Te, Mo, etc.

TABLE F

Metallic Globule (or Scales) on Charcoal

1. Brittle—Antimony.
2. Bright and malleable—Tin.
3. Malleable, easily fusible ; leaves a mark on paper—Lead.
4. Brittle and fusible—Bismuth.
5. White and malleable—Silver.
6. Copper-red—Copper.
7. Yellow—Gold.

TABLE G

Colour of Borax Bead

Oxidising Flame.	Reducing Flame.	Indicates
1. Blue.	Blue.	Cobalt.
2. Green when hot, blue when cold.	Colourless ; opaque red with much of the substance.	Copper.
3. Orange-red to yellow.	Green.	Chromium.
4. Brownish-red when hot, yellow when cold.	Green when cold.	Iron ; also (paler) Uranium.
5. Violet when hot, brown when cold.	Grayish, opaque.	Nickel.
6. Yellowish when hot, colourless when cold.	Colourless or gray.	Bismuth.
7. Amethyst.	Nearly colourless.	Manganese.
8. Yellow when hot, greenish when cold.	Brownish when hot, green when cold.	Vanadium.
9. Yellow when hot, colourless when cold.	Yellowish-brown.	Titanium.
10. Colourless.	Brown.	Molybdenum.
11. Colourless.	Yellow to brown.	Tungsten.
12. Rose.	Rose.	Didymium.
13. Yellow.	Colourless.	Cerium.

TABLE H

Colour of Microcosmic Salt Bead

Oxidising Flame.	Reducing Flame.	Indicates
1. Red to yellow.	Red to yellow.	Nickel.
2. Greenish.	Green.	Molybdenum.
3. Yellow to green.	Green.	Uranium.
4. Colourless.	Yellow, violet when cold.	Titanium.
5. Colourless.	Brown.	Niobium.
6. Yellow to colourless.	Blue.	Tungsten.
7. Green.	Green.	Chromium.

8. Microcosmic salt is especially useful in the detection of silicates, which are all decomposed by it ; the metallic oxides are dissolved while the silica remains as an insoluble cloud especially noticeable while the bead is hot.

TABLE K

Colour of Residue heated with Cobalt Nitrate

1. Red indicates Magnesium (the residue glows during ignition).
   ,, ,, Barium (red while hot).
   ,, ,, Tantalum (red when cold).
2. Green ,, Zinc (except the silicate).
   ,, ,, Titanium (yellowish).
   ,, ,, Tin (bluish).
3. Violet ,, Zirconium.
4. Blue ,, Aluminium (also Silicon).

The only reliable reactions are those of Zinc and Aluminium.

Tables of Physical Properties

TABLE I

Minerals arranged according to their Mean Refractive Index in Na-light

(*Names in italics are not mentioned in the table on pp. 535-548*)

1·31, Ice.
1·35, Wulfenite.
,, Cryolite.
1·38, Sellaite.
1·43, Fluor.
1·45, Nitre.
,, Opal.
,, Epsomite.
1·46, Kalinite.
,, Kieserite.
,, Nosean.
,, Sassolite.
,, Nitratine.
,, Borax.
1·47, Gmelinite.
,, Heintzite.
,, Fluellite.
,, Thenardite.
,, Melanterite.
,, Picromerite.
,, Kainite.
,, Aluminite.
,, Carnallite.
,, *Hopeite.*
,, Goslarite.
,, *Boussingaultite.*
1·48, Tridymite.
,, *Faujasite.*
,, *Glaserite.*
,, Phillipsite.
,, Natrolite.
1·48, *Morenosite.*
,, Sodalite.
1·49, Thaumasite.
,, Analcite.
,, Sylvite.
,, Allophane.
,, *Cyanochroite.*
,, *Löweite.*
,, Aphthitalite.
1·50, Stilbite.
,, Scolecite.
,, Haüyne.
,, Blödite.
,, Chabazite.
,, *Levyne.*
,, *Ulexite.*
,, Heulandite.
,, *Nesquehonite.*
,, Struvite.
,, Prosopite.
1·51, Trona.
,, Leucite.
,, Thomsonite.
,, Harmotome.
,, Petalite.
,, Epistilbite.
,, Pyromorphite.
,, Brewsterite.
,, Northupite.
1·52, Cancrinite.
,, *Davyne.*
1·52, Newberyite.
,, *Hautefeuillite.*
,, Gaylussite.
,, Laumontite.
,, *Mellite.*
,, Orthoclase.
,, Pollucite.
1·53, Microcline.
,, Anorthoclase.
,, Gypsum.
,, Pirssonite.
,, *Fischerite.*
,, *Hydromagnesite.*
,, Albite.
,, Langbeinite.
,, Chalcanthite.
,, Witherite.
,, Apophyllite.
1·54, Nepheline.
,, Gismondite.
,, Hyalophane.
,, Sulphoborite.
,, Oligoclase.
,, Kaolinite.
,, Cordierite.
,, Salt.
1·55, *Johnstrupite.*
,, Serpentine.
,, Eudidymite.
,, Quartz.
,, Syngenite.

1·55, Gibbsite.
,, Chalcedony.
,, Andesine.
,, Polyhalite.
,, *Dipyre.*
,, Coquimbite.
,, *Mizzonite.*
1·56, Beryllonite.
,, Labradorite.
,, Pinnoite.
,, Tale.
1·57, Epididymite.
,, Bertrandite.
,, Brucite.
,, Parisite.
,, Calcite.
,, Wagnerite.
,, *Fibroferrite.*
,, *Bastite.*
,, Marialite.
,, Bauxite.
,, *Pandermite.*
,, Alunite.
1·58, Pennine.
,, Meionite.
,, Augelite.
,, Anorthite.
,, Scapolite.
,, Pyrophyllite.
,, Cacoxenite.
,, *Corundophilite.*
,, Muscovite.
,, Ferronatrite.
1·59, Beryl.
,, Anhydrite.
,, Colemanite.
,, Leucophane.
,, Clinochlore.
,, Pharmacolite.
,, Biotite.
,, Zinnwaldite.
,, Sussexite.
,, *Garnierite.*
,, Amblygonite.
,, Vivianite.
,, Dolomite.
,, Hambergite.
1·60, Lepidolite.
,, Paragonite.
,, Humite.
,, *Meliphane.*
1·61, Eudialyte.
,, Phlogopite.
1·61, Torbernite.
,, *Pittieite.*
,, *Gummite.*
,, *Glauconite.*
,, Turquoise.
,, Pectolite.
1·62, Herderite.
,, Topaz.
,, Tremolite.
,, *Eucolite.*
,, Uranocircite.
,, Autunite.
,, Hemimorphite.
,, Chondrodite.
,, Celestite.
,, Lazulite.
1·63, Carpholite.
,, Tourmaline.
,, Actinolite.
,, Prehnite.
,, *Richterite.*
,, *Gedrite.*
,, Wollastonite.
,, *Celadonite.*
,, *Pargasite.*
,, Annabergite.
,, Erythrite.
,, Melilite.
,, Anthophyllite.
,, Aragonite.
,, Danburite.
1·64, Andalusite.
,, Barytes.
,, *Uralite.*
,, Sarcolite.
,, Zeunerite.
,, Sal-ammoniac.
,, Apatite.
,, Glaucophane.
,, Margarite.
1·65, Datolite.
,, Hornblende.
,, Clintonite.
1·66, Tellurite.
,, *Seybertite.*
,, Forsterite.
,, Euclase.
,, Pyrosmalite.
,, Jadeite.
,, Phenacite.
1·67, Spodumene.
,, Sillimanite.
,, Boracite.
1·67, *Rinkite.*
,, Spangolite.
,, Enstatite.
,, Strontianite.
,, Nephrite.
,, Monticellite.
,, Gehlenite.
,, Haidingerite.
,, Adelite.
,, *Prolectite.*
,, Lawsonite.
1·68, Kornerupine.
,, Axinite.
,, Olivine.
,, Triphylite.
,, *Diallage.*
,, *Harstigite.*
,, Diopside.
1·69, Barytocalcite.
,, Bromlite.
,, *Troostite.*
,, *Wöhlerite.*
,, *Fuggerite.*
,, Dioptase.
1·70, Hypersthene.
,, Tyrolite.
,, Willemite.
,, Euchroite.
,, Gadolinite.
,, *Barkevikite.*
,, Gerhardtite.
,, Astrophyllite.
,, Zoisite.
1·71, *Arfvedsonite.*
,, Pharmacosiderite.
,, *Rhodochrosite.*
,, Spinel.
,, Sapphirine.
1·72, Vesuvianite.
,, Clinozoisite.
,, Magnesite.
,, Chloritoid.
,, Babingtonite.
,, *Pajsbergite.*
,, Xenotime.
,, Cyanite.
,, Trimerite.
,, Rhodonite.
,, Augite.
,, Diaspore.
,, Hæmatolite.
1·73, *Ottrelite.*
,, *Ganophyllite.*

1·73, *Piedmontite.*
,, *Phosphosiderite.*
1·74, Allanite.
,, Periclase.
,, Ilvaite.
,, *Thalenite.*
,, Helvite.
,, Staurolite.
,, Hedenbergite.
,, Libethenite.
1·75, Chrysoberyl.
,, Chalybite.
,, Arsenolite.
,, *Pleonaste.*
1·76, Grossular.
,, Epidote.
,, Corundum.
1·77, Gahnite.
,, Pyrope.
1·78, Inesite.
,, Ænigmatite.
,, Hercynite.
,, Acmite.
1·78, Essonite.
,, Almandine.
1·79, Allactite.
,, *Ardennite.*
1·80, Tephroite.
1·81, Spessartite.
,, Strengite.
,, Monazite.
1·83, Uvarovite.
,, Olivenite.
,, Descloizite.
,, Linarite.
1·84, Scorodite.
1·85, Caledonite.
1·88, Malachite.
,, Anglesite.
1·89, Titanite.
1·92, Scheelite.
1·95, Zircon.
1·99, Cerussite.
2·00, Cassiterite.
,, Cerargyrite.
2·01, Sulphur.
2·01, Senarmontite.
2·13, Phosgenite.
2·15, *Paralaurionite.*
2·18, Iodyrite.
2·22. Stolzite.
2·25. Bromyrite.
2·31, Calomel.
2·35, Pyrophanite.
2·37, Blende.
2·38, Perovskite.
2·40, Wulfenite.
2·42, Diamond.
,, Crocoite.
2·53, Anatase.
,, Brookite.
2·60, Raspite.
2·69, Greenockite.
2·76, Rutile.
2·85, Cuprite.
2·94, Proustite.
2·98, Pyrargyrite.
3·02, Cinnabar.

TABLE II

Minerals arranged according to their Birefringence

Uniaxial Positive

·001 Gmelinite.
·002 Apophyllite.
·003 Pennine.
,, *Löweite.*
·004 Ice.
,, *Davyne.*
·005 Eudialyte.
·008 Aphthitalite.
,, Coquimbite.
·009 Quartz.
·010 Zincite.
,, Iodyrite.
·012 Sellaite.
·016 Phenacite.
,, Scheelite.
·018 Tridymite.
·020 Mimetite.
,, Wolframite.
,, Wurtzite.
·021 Brucite.
·026 Phosgenite.
·055 Ferronatrite.
·056 Dioptase.
·062 Zircon.
·099 Cassiterite.
·101 Parisite.
·287 Rutile.
·347 Cinnabar.
·683 Calomel.

Uniaxial Negative

·001 Vesuvianite.
·002 Chabazite.
,, *Levyne.*
·003 *Eucolite.*
·004 Apatite.
·005 Nepheline.
,, Melilite.
·006 Pyromorphite.
·007 Beryl.
·008 Corundum.
·010 Vanadinite.
·015 *Mizzonite.*
·017 Tourmaline.
·019 *Meliphane.*
·021 Scapolite.
·028 Canerinite.
,, *Mellite.*
·036 Meionite.
·038 Thaumasite.
·053 Spangolite.
·061 Anatase.
·086 Stolzite.
·098 Wulfenite.
·172 Calcite.
·189 Dolomite.
·200 Calamine.
·203 Pyrargyrite.
·222 Rhodochrosite.
·241 Chalybite.
·250 Nitratine.
,, Hæmatite.
·268 Proustite.
·270 Pyrophanite.

Biaxial Positive

·002 Apophyllite.	·012 Petalite.	·025 *Crocidolite.*
·005 Eudidymite.	,, *Johnstrupite.*	,, Wavellite.
,, *Harstigite.*	·013 Natrolite.	·028 Colemanite.
,, Harmotome.	·014 Augelite.	,, Thomsonite.
·006 Clinozoisite.	·015 *Ottrelite.*	·030 Diopside.
,, Zoisite.	,, Chloritoid.	·032 Chondrodite.
·007 Heulandite.	·016 Anglesite.	·033 Prehnite.
·008 Albite.	·019 Euclase.	·036 Olivine.
·009 Chrysoberyl.	,, Hedenbergite.	·038 Pectolite.
,, Enstatite.	,, Lawsonite.	·043 Anhydrite.
,, Topaz.	·020 *Fouquéite.*	·045 Monazite.
,, Celestite.	,, *Ardennite.*	·050 Crocoite.
·010 *Quartzine.*	·021 Augite.	·055 Astrophyllite.
,, Staurolite.	,, Spodumene.	·071 Pirssonite.
,, Gypsum.	,, Sillimanite.	·072 Hambergite.
·011 Clinochlore.	·022 Glaucophane.	·121 Titanite.
,, Boracite.	,, Hemimorphite.	·160 Brookite.
·012 *Hainite.*	·023 Gibbsite.	·200 *Molybdite.*
,, Brewsterite.	·024 Anthophyllite.	,, Chessylite.
,, Barytes.	,, *Diallage.*	·290 Sulphur.

Biaxial Negative

·004 Epididymite.	·012 Clintonite.	·029 Herderite.
·005 Danburite.	,, Anorthite.	·030 Realgar.
·006 Sapphirine.	·013 Hypersthene.	,, Chalcanthite.
,, Stilbite.	,, *Thalenite.*	,, *Lavenite.*
,, Orthoclase.	,, Wagnerite.	·031 *Nesquehonite.*
·007 Microcline.	·014 Wollastonite.	·032 Allanite.
,, Andesine.	·016 Cyanite.	·036 Lazulite.
·008 Oligoclase.	·017 Sulphoborite.	·038 Muscovite.
,, Kaolinite.	·018 Amblygonite.	·040 Talc.
,, Cordierite.	·019 *Pargasite.*	,, Pyrophyllite.
,, Labradorite.	·022 *Seybertite.*	,, Epidote.
·009 Axinite.	,, Carpholite.	·044 Biotite.
,, Beryllonite.	,, Atacamite.	·045 Datolite.
·010 Dumortierite.	·024 *Ganophyllite.*	·070 Leadhillite.
,, Trimerite.	·025 *Morenosite.*	·072 Hornblende.
,, Epistilbite.	,, Actinolite.	·091 Okenite.
,, Rhodonite.	·026 Borax.	·152 Strontianite.
·011 Andalusite.	·027 Leucophane.	·156 Aragonite.
,, Serpentine.	,, Goslarite.	·172 Nitre.
·012 Kornerupine.	·028 Tremolite.	·200 Malachite.
,, Laumontite.	,, Epsomite.	·274 Cerussite.

TABLE III

Minerals arranged according to the value of 2E

(The angles relate to Na-light unless otherwise specified)

7° 51′ Biotite.
8° 58′ Nitre.
9° 50′ Bromlite (red light).
10° 0′ Sassolite.
10° 36′ Strontianite.
13° 32′ Allactite.
14° 8′ Glauberite.
17° 8′ Cerussite.
19° 1′ Talc.
20° 23′ Clintonite.
20° 32′ Leadhillite (red).
20° 45′ Sanidine (red).
23° 15′ Barytocalcite (red).
26° 30′ Witherite (red).
27° 0′ Serpentine.
28° 25′ Monazite.
30° 0′ Clinochlore.
30° 16′ Brookite.
30° 54′ Aragonite.
41° 53′ *Ganophyllite.*
43° 0′ Zoisite (red).
44° 0′ Sillimanite (red).
44° 23′ Syngenite.
47° 0′ Eudidymite.
48° 14′ Pirssonite.
49° 40′ Epididymite.
50° 0′ Göthite (blue).
50° 34′ Dumortierite.
51° 38′ Gaylussite (red).
52° 24′ Laumontite (red).
52° 30′ Stilbite (blue).
52° 30′ Titanite.
55° 0′ *Wapplerite.*
55° 44′ Scolecite.
56° 30′ *Alurgite.*
57° 50′ Zinnwaldite.
59° 23′ Borax.
59° 24′ Cryolite.
59° 30′ Wagnerite.
60° 0′ *Catophorite.*
60° 0′ Ænigmatite.
60° 56′ Struvite.
60° 57′ Autunite.
61° 11′ Euchroite.
63° 3′ Amarantite.
64° 1′ Barytes.
64° 22′ *Morenosite.*
65° 30′ Kornerupine.
66° 0′ *Herrengrundite.*
66° 5′ *Serpierite.*
67° 37′ Hornblende (Basaltic).
69° 36′ Thomsenolite.
70° 0′ Muscovite.
70° 0′ *Hæmafibrite.*
70° 17′ *Ardennite.*
70° 20′ Newberyite.
70° 40′ Wollastonite (red).
71° 3′ Goslarite.
71° 24′ Lepidolite.
71° 30′ Anhydrite.
71° 40′ Anorthoclase.
72° 0′ Baddeleyite.
74° 2′ Picromerite.
74° 15′ Leucophane.
74° 25′ Childrenite.
75° 35′ Epistilbite.
76° 0′ *Salvadorite.*
76° 12′ *Cyanochroite.*
77° 28′ *Boussingaultite.*
77° 53′ *Rinkite.*
78° 18′ Epsomite.
78° 39′ Hemimorphite.
80° 0′ *Corundophilite.*
83° 0′ Sarcinite.
84° 15′ *Nesquehonite.*
84° 42′ Augelite.
84° 43′ Chrysoberyl.
85° 7′ *Hopeite.*
85° 35′ Glaucophane.
86° 0′ Thomsonite (red).
86° 21′ Amblygonite.
87° 44′ Mascagnite (red).
87° 59′ Euclase.
88° 0′ *Hautefeuillite.*
88° 32′ Heulandite.
88° 38′ Celestite.
89° 18′ Malachite.
90° 0′ Kaolinite.
90° 0′ Kieserite.
90° 28′ *Vallétie.*
93° 1′ Chalcanthite.
94° 0′ Brewsterite (red).
95° 0′ *Crocidolite.*
95° 8′ Colemanite.
95° 14′ Gypsum (red) at 20°.
99° 0′ Natrolite.
100° 0′ Pyrophyllite.
101° 7′ Hypersthene.
102° 50′ Prosopite.
106° 18′ *Fischerite.*
106° 40′ Adelite.
107° 30′ *Pargasite* (red).
108° 1′ Lanthanite (red).
108° 34′ Keilhauite.
108° 52′ Carpholite.
111° 20′ Augite.
111° 50′ Chloritoid (red).
112° 12′ Diopside.
112° 42′ Natron.
114° 30′ Margarite.
115° 1′ Carnallite (red).
118° 54′ Blödite (red).
120° 0′ Pachnolite.
120° 12′ Orthoclase.
120° 40′ Topaz.
121° 1′ Beryllonite.
121° 22′ Herderite.
122° 48′ Mirabilite (red).
124° 40′ *Johnstrupite.*
125° 0′ *Warwickite.*
125° 0′ Xanthoconite.
125° 16′ Cordierite.
126° 26′ *Phosphosiderite.*
127° 2′ Wavellite.
129° 32′ Scorodite.
132° 57′ Liroconite.
134° 27′ Acmite.
135° 26′ Prehnite.
136° 25′ Lazulite (red).
137° 7′ Trona.
141° 0′ Kainite.
141° 14′ Clinoclase (green).
143° 14′ Vivianite.
144° 52′ Anglesite.
144° 52′ Bertrandite.
146° 24′ Enstatite.
150° 12′ *Thalenite.*
150° 40′ Sapphirine.
151° 0′ Chessylite (blue).
152° 42′ Thenardite.
156° 48′ Hyalophane.
157° 51′ Axinite (red).
161° 48′ Tephroite (red).
166° 2′ *Wöhlerite* (red).
170° 20′ Datolite.
173° 52′ Hureaulite (red).

Minerals arranged according to the value of 2V

54° 3′ Crocoite.
59° 52′ Hedenbergite.
69° 5′ Sulphur.
73° 39′ Epidote.
75° 0′ Hübnerite (red).
76° 12′ Rhodonite.
79° 46′ *Lavenite.*
79° 59′ Homilite (red).
79° 59′ Linarite.
80° 4′ Actinolite.
81° 8′ Libethenite.
81° 40′ Clinozoisite.
82° 22′ Ludlamite.
82° 30′ Cyanite (red).
82° 37′ Caledonite.
82° 43′ Gismondite.
83° 29′ Trimerite.
83° 34′ Petalite.
83° 41′ Microcline.
84° 6′ Lawsonite.
84° 20′ Diaspore.
84° 30′ Andalusite.
85° 28 Gadolinite.
86° 10′ Forsterite.
86° 13′ Melanterite.
87° 10′ Hambergite.
88° 16′ Tremolite.
88° 23′ Danburite.
88° 46′ Anthophyllite.
88° 46′ Staurolite (red).
88° 54′ Olivine.
89° 33′ *Harstigite.*
90° 0′ Boracite.

Minerals arranged according to the value of 2H.

57° 45′ Römerite.
64° 58′ Spodumene.
65° 3′ Lanarkite (red).
65° 21′ Claudetite.
78° 30′ Humite.
79° 30′ Triphylite (blue).
80° 49′ Durangite.
82° 0′ Albite.
82° 48′ Jadeite.
84° 30′ Pseudobrookite.
84° 50′ Anorthite (red).
84° 54′ Phillipsite.
85° 15′ Clinohumite.
85° 52′ *Pisanite.*
87° 2 Harmotome (red).
88° 48 Chondrodite.
92° 58′ Realgar.
93° 11′ Atacamite.
95° 6′ Brochantite.
95° 27′ Triplite.
98° 30′ *Hyalotekite.*
104° 27′ Heintzite.
104° 31′ Erythrite.
106° 6′ Olivenite.
107° 28′ Symplesite.
*108° 34′ Adamite (red).
*112° 20′ Pharmacolite.
*114° 15′ Copiapite.
*119° 23′ *Molybdite.*
*124° 33′ Astrophyllite.
*140° 8′ Tellurite.
*144° 0′ Pectolite.

* These are the obtuse angles.

TABLE IV

Minerals arranged according to their Specific Gravity

0·92 Ice.
1·03 *Copalite.*
1·07 *Elaterite.*
,, *Succinite.*
,, *Uintahite.*
1·10 *Libollite.*
1·40 *Mineral Coal.*
1·44 Natron.
1·45 Teschemacherite.
1·48 Mirabilite.
,, Sassolite.
1·50 *Collyrite.*
,, Tschermigite.
1·53 Sal-ammoniac.
1·54 *Lansfordite.*
1·55 *Anthracite.*
,, Thermonatrite.
1.60 Carnallite.
1·61 Stercorite.
1·64 *Mellite.*
1·65 Bischofite.
,, Ulexite.
1·66 Aluminite.
1·68 Struvite.
1·70 Borax.
,, Alunogen.
,, *Boussingaultite.*
1·75 Kalinite.
,, Epsomite.
,, *Cyprusite.*
,, *Ettringite.*
1·77 Mascagnite.
1·78 *Apjohnite.*
1·81 *Ihleite.*
1·84 *Nesquehonite.*
,, *Fibroferrite.*
1·87 Allophane.
,, *Chloropal.*
1·88 Thaumasite.
,, *Mendozite.*
1·89 Melanterite.
,, *Hannayite.*
1·90 *Ascharite.*
1·92 *Faujasite.*
1·94 Gaylussite.
,, Evansite.
1·95 Halotrichite.
,, *Hydroboracite.*
1·98 Sylvite.
,, *Kröhnkite.*
2·00 Goslarite.
,, *Sepiolite.*
,, *Erionite.*
,, *Morenosite.*
,, *Schrötterite.*
2·04 Melanophlogite.
,, *Diadochite.*
2·07 *Hydrotalcite.*
,, Sulphur.
2·08 *Mordenite.*

2·09 Coquimbite.
,, Botryogen.
2·10 Gmelinite.
,, Deweylite.
,, Newberyite.
,, *Halloysite.*
,, Copiapite.
2·11 *Quetenite.*
,, Amarantite.
2·12 Chrysocolla.
,, Chabazite.
,, Castanite.
,, *Quenstedtite.*
2·13 Kainite.
,, Nitre.
,, Trona.
,, *Levyne.*
,, Heintzite.
2·14 Salt.
2·15 Opal.
,, Picromerite.
,, Sideronatrite.
2·16 Graphite.
,, *Hydrogiobertite.*
,, *Hydromagnesite.*
,, Stilbite.
2·17 Fluellite.
,, Römerite.
2·20 Heulandite.
,, *Hydrophilite.*
,, Darapskite.
,, Phillipsite.
2·21 Chalcanthite.
,, Brushite.
2·22 Chrysotile.
2·23 *Laubanite.*
,, Natrolite.
2·24 *Cimolite.*
2·25 Epistilbite.
,, Blödite.
,, *Lindackerite.*
2·26 Nitratine.
,, *Zincaluminite.*
,, Gismondite.
,, Analeite.
2·27 *Saponite.*
2·28 Okenite.
2·29 Mesolite.
,, *Metabrushite.*
,, Poonahlite.
2·30 *Glauconite.*
,, *Hydronephelite.*
,, Scolecite.
2·30 *Jefferisite.*
,, Laumontite.
,, *Humboldtite.*
,, Tridymite.
,, Sodalite.
2·32 Wellsite.
,, Gypsum.
,, Nosean.
2·33 Wavellite.
,, *Felsöbanyite.*
2·34 *Kehoeite.*
2·35 Hambergite.
,, *Pittieite.*
,, Pirssonite.
,, Gibbsite.
,, Apophyllite.
,, Thomsonite.
2·37 *Newtonite.*
2·38 Northupite.
,, *Löweite.*
2·39 Brucite.
2·40 Dawsonite.
2·41 *Genthite.*
,, *Pholidolite.*
2·42 Sulphoborite.
,, *Indianite.*
,, Lazurite.
,, Colemanite.
2·43 *Daryne.*
,, *Hautefeuillite.*
2·44 *Microsommite.*
2·45 Petalite.
,, Brewsterite.
,, Haüyne.
,, Canerinite.
2·46 *Fischerite.*
2·47 Harmotome.
,, *Hoernesite.*
,, Leucite.
2·48 *Wapplerite.*
2·49 *Phacelite.*
,, Sulphohalite.
2·50 *Spadaite.*
,, Carphosiderite.
,, *Peganite.*
2·51 *Callainite.*
2·52 Kieserite.
2·53 *Metavoltine.*
,, Chaleophyllite.
,, *Calcoferrite.*
2·54 *Connarite.*
,, *Sphærite.*
2·55 Epididymite.
2·55 Eudidymite.
,, *Howlite.*
,, Bauxite.
2·56 Serpentine.
,, Hanksite.
,, Ferronatrite.
,, Mierocline.
,, Elpidite.
,, Orthoclase.
2·57 Marialite.
,, Milarite.
2·58 Anorthoclase.
,, Ralstonite.
,, *Barrandite.*
2·60 Nepheline.
,, Bertrandite.
,, Lanthanite.
,, Syngenite.
,, Kaolinite.
,, Kaliophilite.
2·62 Chaleedony.
,, *Mizzonite.*
2·63 Vivianite.
,, *Zaratite.*
,, Cordierite.
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DESCRIPTION OF PLATES

Plate I.

The interference figure of a section of orthoclase viewed successively in blue, green, and red monochromatic light.

With increasing wave-length the rings become wider, the interference in the centre corresponding to about one wave-length of blue, and about $\frac{2}{3}$ of a wave-length of red light.

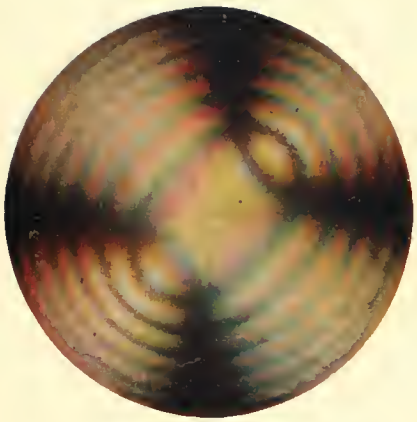
Plate II.

The interference figure of the same section in white light.

This displays inclined dispersion, with $\rho < v$, the hyperbola being fringed with blue on the convex side, and the rings being symmetrical to a line joining the optic axes.

The double refraction is weak, the section having a thickness of 3 mm.

Plate II. has been made by printing the three black figures of Plate I. upon each other in yellow, red, and blue inks respectively.



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